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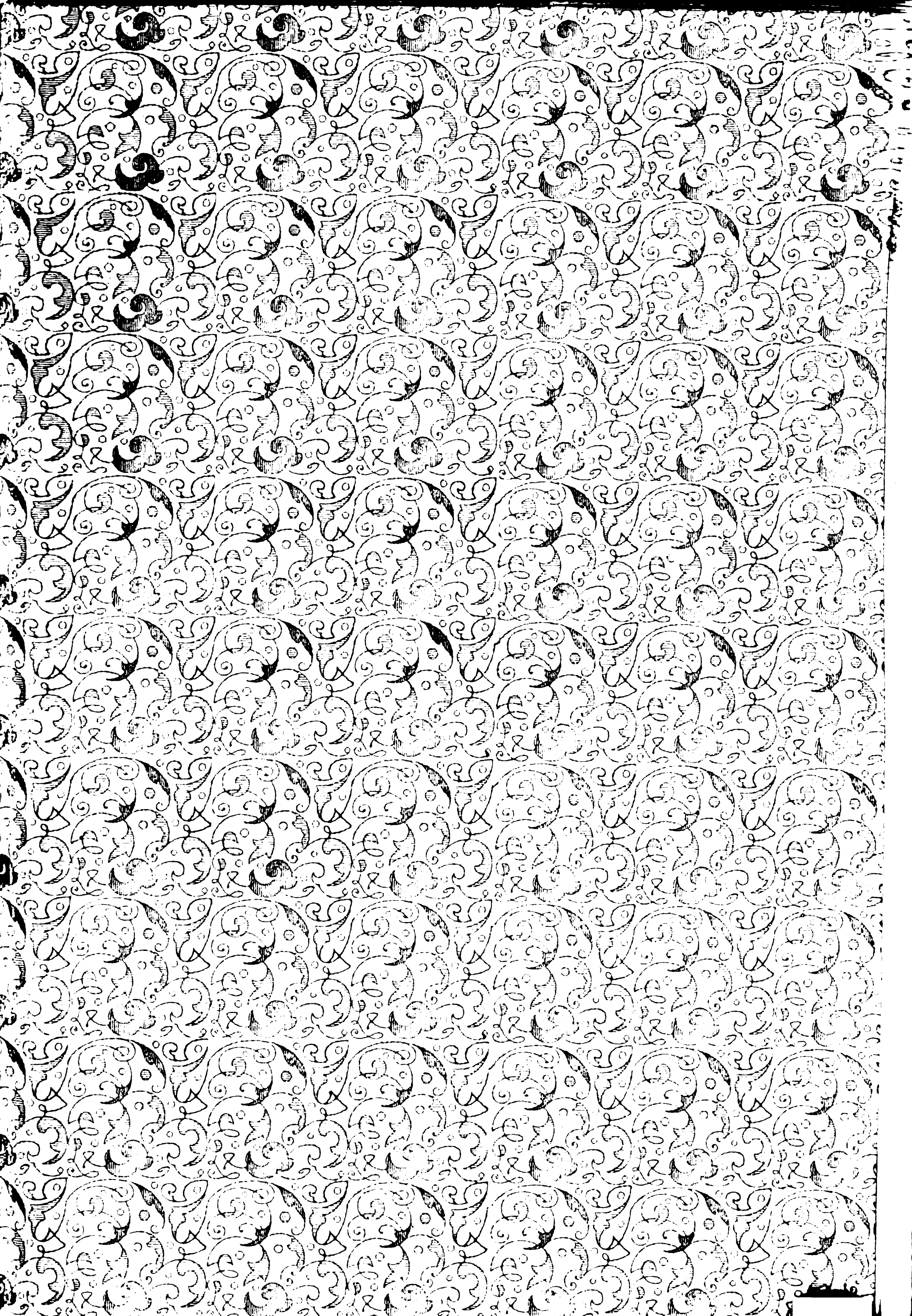

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SEISMOLOGICAL SOCIETY OF AMERICA

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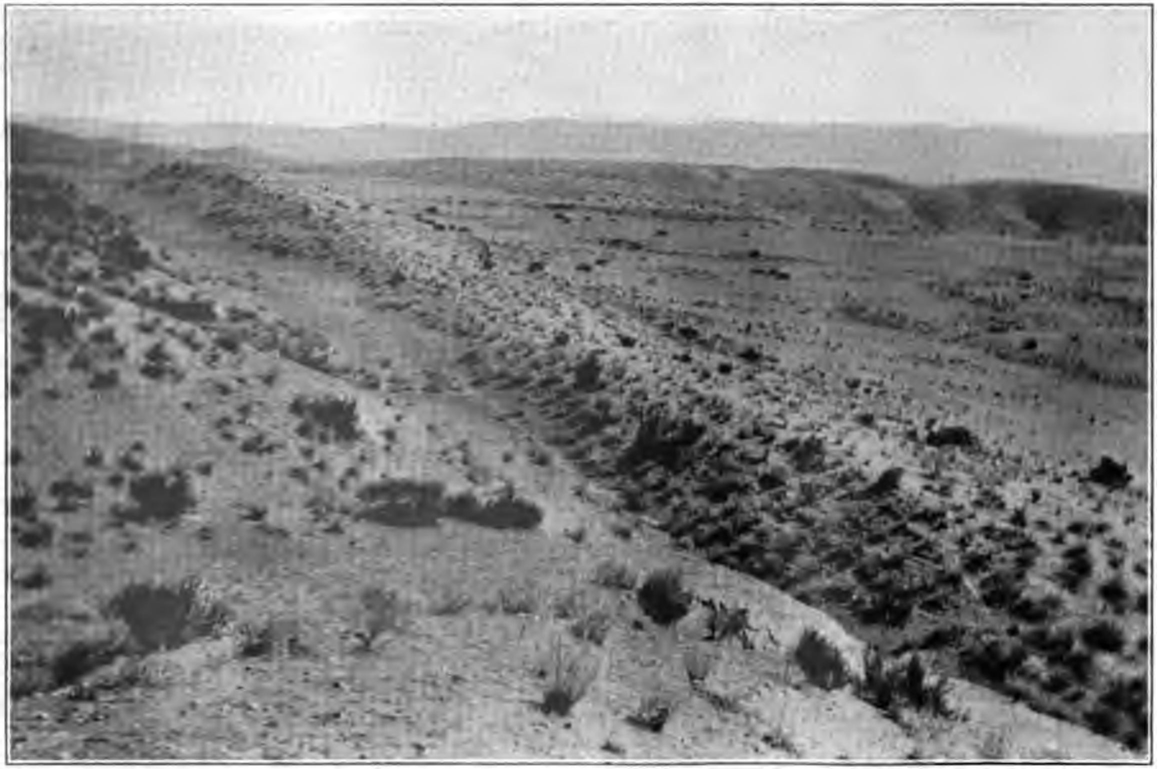

The low ridge along the earthquake rift in the southeast end of Carrisa plains, southwest of McKittrick, on section 11, 32 s. 21 e., San Luis Obispo county, California. The fault follows the steeper left side of the ridge. The view looks southeast. Photograph by Ralph Arnold, August 1911.

The Bulletin of the
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THE SEISMOLOGICAL WORK OF JOHN MILNE.

By Comte de Montessus de Ballore.

John Milne, the seismologist of world-wide fame, died a few months ago. In European countries Milne's work has been quoted in every seismological investigation published since 1880; and seismologists always relied implicitly upon his papers, and no doubt they will long continue so to rely upon him. This means that a full account of the regretted master's investigations would be a history of the advance in seismologic science during the last thirty years. But important as his work has been it is not an easy task to analyze it, for he never brought it together into a general treatise; if we except a small but very interesting popular volume,

1. "Seismology." International Science Series, London, 1898.

To this volume Milne attached no importance, as is shown by what he wrote when sending us a copy of it. Of course this was due to exaggerated scruples, for any professional seismologist can learn much from Milne's "Seismology," a volume which has been a sort of supplement to another of the same scientific series,

2. "Earthquakes and other earth movements." International Science Series, London, 1883,

and which, I believe, has passed through at least four editions.

We realize that at this early date Milne already held full dominion over the subject to which he was to devote all his life. He went to Japan in 1875, at the age of twenty-five years, a mining engineer appointed by the Mikado's government, which at this time intended to introduce among the people western education and civilization. By 1880 Milne was already regarded as a fully qualified and well informed seismologist. Five years had been enough for him to grasp the seismological science of this epoch,—the science of Mallet, Perrey, de Rossi, and Suess; and from the first day of his arrival in Japan he had begun to attack the earthquake problem in the Empire of the Rising Sun, a land in which earth disturbance is a sort of national phenomenon.

On the 26th day of March, 1880, at the first meeting of the famous Seismological Society of Japan, which he had the enthusiastic initiative to found, Milne spoke of the seismological labor to be undertaken:

3. "Seismic science in Japan." *Transactions of the Seismological Society of Japan,* April-June, 1880, 1, Pt. 1. 3. Yokohama. (This periodical will be indicated by the letters *T. S. S. Japan.*)

Milne's address on that occasion was a clear statement of the scientific knowledge relating to earthquakes that had been gathered up to that time; it also indicated the program of the investigations to be undertaken, in every way that his acute and positive mind had suggested, and which he followed successfully and imperturbably all his life.

Above all, Milne was a man of observation and experiments; and in spite of his training as a geologist he showed himself a natural philosopher, rather than a geologist. He used mathematics without abusing it, employing it for representing or calculating the geometrical or mechanical elements of earthquake phenomena; and he never allowed himself to be misled by it in regard to theoretical views. He did not delight in pompous generalizations that are often as ephemeral as brilliant, but he observed and experimented ceaselessly and carefully. From the data thus gained he reached only strictly warranted conclusions, and he discerned clearly the possible or the probable ones; and when new ways seemed opened by his observations, he never hesitated about accepting them. To Milne's labor as a whole we can apply the old adage, so often disregarded, that theories fade away, but the facts of observation remain. Inquiry into the more profound causes did not preoccupy his mind, for he believed they are beyond our reach; so that although he was a steady defendant of the tectonic theory of earthquakes, only in a few passages did he disclose his thoughts on this subject. We quote the following, which is the most explicit of his with which we are acquainted (1, p. 38):

> The general conclusions at which we arrive are that the majority of earthquakes, including all of any magnitude, are spasmodic accelerations in the peculiar folding or *creep* of rock masses; a certain number, particularly those originating off the mouths of large rivers like the Tonegawa in Japan, may result from the sudden yielding of the more or less horizontal flow of deeply seated material, the immediate cause of which is overloading by the deposition of sediments; whilst a few, which are comparatively feeble and shake limited areas, are due to explosions of volcanic foci.

So Milne was all his life a decided partisan of the tectonic or geologic origin of earthquakes, and at the same time he defended the independence between the volcanic and seismic phenomena, a fact which yet remains hardly admitted by many people in spite of observational evidence. In many instances, also, he insisted, though briefly, upon the relationship between the seismic disturbances and changes of level, that is to say, the bradyseisms. We ought to note also that he does not speak of earthquakes as being caused by subterranean sinkings or fallings,—which we often meet with in the seismological literature and which is now nothing more than an old and discredited theory.

Milne's theory, quoted above, in regard to earthquakes supposed to be caused by a sort of isostasy in the fluvial sediments deposited in front of the mouths of the large rivers, has not been accepted in seismological circles, except by Hogben and Middlemiss. The former applied it to the earthquakes of the eastern coast of southern New Zealand, whilst the latter adapted it to the Kangra, Himalaya, earthquake of April 5, 1905. Milne did not mention this earthquake, except in connection with the breaking of submarine cables, as we shall point out further on.

Milne's seismological works are scattered through so great a number of papers and memoirs that an analysis of them all would be an enormous task. We must therefore undertake it in a bibliographical form; that is to say, we shall arrange the papers before alluded to in a certain number of titles or sections, more or less conventional, and we shall endeavor to summarize the thoughts of the master only on the fundamental problems, but without entering into unimportant details, it being sufficient for these latter to quote the respective papers.

From 1880 to 1892 Milne was the leader of the famous Seismological Society of Japan; and when this broke up, he continued to publish the *Transactions* (16 volumes) as the *Seismological Journal of Japan* (4 volumes, 3127 pages in total). If we omit from both collections 38 pages from anonymous authors, there remains 67 per cent. of pages with his signature; whilst only 23 and 10 per cent. were by other European or Japanese authors respectively.

In 1896 he returned to his own country, and lived at Shide Hill house, Newport, Isle of Wight, where he pursued indefatigably his admirable investigations, in one of the more stable points of the globe. Not satisfied with his restricted seismic domain of Japan, he watched and studied from there the earthquakes of the world as from the apex of modern seismological science. From this time on he published about all of his studies in the "Reports on Seismological Investigations"[1] of the British Association for the Advancement of Science, the texts of which were mostly written by him.

A chronological and bibliographical method was unavoidable, and we have classified Milne's papers as follows:

I. General points of view.
II. Earthquake catalogues.
III. Earthquake monographs.
IV. Instruments and experiments. Seismometrical observations.
V. Seismic movement.
VI. Earth tremors and pulsations.
VII. Geographical and geological points of view.
VIII. Relations between seisms and other phenomena of earth physics.
IX. Aseismic buildings; practical seismology.
X. Relations between earthquakes and variations of the vertical and changes of latitude.
XI. Volcanoes.
XII. Internal heat and state of the globe. Geite. Elasticity of the rocks.
XIII. Seismological miscellanea.
XIV. Bibliography and biography.

I. GENERAL POINTS OF VIEW

In consequence of the great range of Milne's papers, we ought not to be surprised if, even in his writings of a more general character, he has not expounded any general theory of earthquakes.

4. "Seismology in Japan." *Nature,* London, October 1882.

5. "Earthquake literature in Japan." *Japan Gazette,* 1882-83. Seven articles.

6. "Recherches sur les tremblements de terre au Japon." Spécialement imprimé pour le Congrès géologique de Berlin. Yokohama, 1885.

In this paper as in many others, but always without details and almost incidentally, Milne points out that earthquakes originate above all in the regions of recent elevation, a word to be understood in the sense of the French word *surrection.*

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[1] This collection will be indicated by the letters *R. S. I.*

7. "Appendix to Recherches sur les tremblements de terre au Japon." Spécialement imprimé pour le Congrès géologique de Berlin. Berlin, 1885.

8. "Causes of earthquakes." An address delivered at the annual meeting of the Rigaku-Kyokai (Society of Sciences). Read at Kôtô-Chugakkô; October 16, 1886.

9. "On certain seismic problems demanding solution." *T. S. S. Japan*, 1888, **12**, 107.

10. "Abstract of a report to the British Association for the Advancement of Science." *S. J. Japan*, **2**; *T. S. S. Japan*, 1893, **18**, 93.

11. "Recent advances in seismology." Royal Institution lectures, February 1897.

12. "Recent advances in seismology." Backerian lectures. *Proc. Roy. Soc. London*, 1906, A. **78**, 365.

Both papers are clear and interesting, but they are little more than popular lectures.

II. Earthquake Catalogues

Milne has published numerous earthquake catalogues, both for Japan and for other parts of the world, which furnish a solid foundation for statistical investigations of all kinds.

13. "Investigations of the earthquake phenomena in Japan." *Reports of the British Association for the Advancement of Science*, 1881 to 1898, eighteen reports.[2]

In the third of these reports, Milne announced that there is an earthquake every half-hour on the average, a frequency that afterwards he had to more than double.

14. "Notes on the great earthquakes of Japan." *T. S. S. Japan*, 1881, **13**, 65.

Here we have to deal with a catalogue of Japanese earthquakes within historical times, from 295 before the Christian era down to 1872. From this extensive catalogue Milne made a brief, but very interesting, critical summary of the bibliographical and original Japanese seismic papers. We ought to mention above all the diagram of the variations of the seismic activity from the sixth to the nineteenth centuries at Kyôtô, the old chief city of Japan.

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[2] This very important collection will be indicated by the letters *R. B. A. A. S.*

15. "Suggestions for the systematic observation of earthquakes." *T. S. S. Japan,* 1882-83, **4**, 85.

This is a scheme for establishing systematic observations over a large region, including the methods and instruments for making the observations.

16. "On 387 earthquakes observed during two years in northern Japan." *T. S. S. Japan,* 1884, **7**, part II, 1.

From October 1881 to October 1883, Milne represented graphically on maps of Japan the areas of disturbance of a very great number of earthquakes, from which it appeared that the majority of those felt along the eastern coasts of that country originate beneath the ocean. This fact shows that it is highly important to investigate in this manner the earthquakes of the maritime countries. Unfortunately many seismological organizations neglect this matter.

17. "Report on earthquake observations made in Japan during the year 1886." *T. S. S. Japan,* 1889, **13**, part I, 91.

18. "Report on earthquake observations made at the Chiri-Kyoku (meteorological department) during the year 1887." An epitome of a translation, with a prefatory note and observations. *T. S. S. Japan,* 1890, **15**, 99.

19. "Report on earthquakes observed in Japan, 1889." *T. S. S. Japan,* 1892, **16**, 81.

20. "A catalogue of 8,831 earthquakes recorded in Japan between 1885 and 1892." *S. J. Japan,* **4**; *T. S. S. Japan,* 1895, **20**. All the volume.

This is a very considerable work, from which Milne has drawn an instructive seismic map of Japan; and he concludes that earthquakes are frequent in Japan where the physiographic lines E-W present a declivity of 1/20 to 1/30 towards the Pacific. It is in this form that he enunciated the now well known relationship between seismicity and terrestrial relief.

21. "A catalogue of destructive earthquakes, A. D. 7 to A. D. 1899." *R. B. A. A. S.,* 1911.

This extensive catalogue contains 4,136 destructive earthquakes of all parts of the world, and is available for statistical and geographical data of great value. It is to be regretted, however, that Milne did not give the details and the original sources for each seismic event reported, a fact which greatly diminishes the importance of this work.

Milne classified the destructive earthquakes by means of three degrees of increasing intensity, and his scale does not differ much from that established by A. Belar upon the occasion of the Messina earthquake of December 28, 1908. It is necessary to reproduce here this very practical scale.

I. It means that an earthquake had an intensity sufficient to crack walls, break chimneys, to shatter old buildings or to produce slight cracks in the ground. It implies an acceleration or rapidity in the change of velocity of the surface of the ground of 1,000 millimeters or three feet per second. This means that each back and forth vibration of the ground corresponded to the jerk we should experience on a truck which commenced to move at the rate of three feet per second, or when moving was suddenly stopped. When this takes place the destructiveness is usually confined to a town or village, and the radius of the area affected will not exceed five miles.[3]

II. With earthquakes of this intensity the acceleration is 1,500 millimeters or five feet per second, and its effect will have a radius of twenty miles.[3] Buildings may be unroofed or shattered and some may fall, the ground may be badly cracked in places, and small landslips occur.

III. Earthquakes with this intensity are those which destroyed towns and devastated districts. The ground has been faulted and fissured, whilst from these openings water, mud and sand may issue. In a hilly country landslips will be common. The acceleration may exceed 3,000 millimeters or ten feet per second. Beyond the mesoseismic area up to a distance of 100 miles the effects produced may be similar to those of class I.

Some interesting remarks follow:

The origin of these earthquakes may generally be assumed to be along the lines of fault or fracture in the earth's crust. Motion sufficient to cause destruction may extend to the right and left of such a line to distances of 100 miles. With earthquakes of class I this distance may not exceed five miles.[3] Should the fault or faults run parallel to a mountain range, which is commonly the case, it is rarely that violent motion will extend beyond such a barrier. Destruction frequently takes place along the length of the valleys.

III. Earthquake Monographs

22. "The earthquake of December 3, 1879." *Japan Gazette,* December 13, 1879.

23. "The earthquake in Japan of February 22, 1880." *T. S. S. Japan,* April-June 1880, 1, Part II, 1; *Japan Gazette,* February 24, 1880.

This is a valuable monograph of an earthquake for the study of which Milne availed himself of all the seismological knowledge of the time.

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[3] This latter conclusion is not exact.

24. "The Peruvian earthquake of May 9, 1877." *T. S. S. Japan*, July-December 1880, 2, 50.

This paper is a model of precision and of acute observation. In it Milne expounds and employs four geometrical methods for calculating the coordinates of the epicenter of a great earthquake, and regarding the concomitant tsunami he presents a solid investigation comparable with those of von Hohsteter and of Geinitz.

25. "The earthquake of December 23, 1880." *The Chrysanthemum*, 1881.

26. "The earthquake of 6 a.m. on July 5, 1881." *Japan Gazette*, July 23, 1881.

27. "A note on the great earthquake of October, 1891." *S. J. Japan*, 1, 127; *T. S. S. Japan*, 1893, 17.

28. "The great earthquake of Japan, 1891." Published with W. K. Burton, Yokohama.

This is the most artistic album ever published on earthquake effects on buildings, ground, and on seismic scenery.

IV. INSTRUMENTS AND EXPERIMENTS. SEISMOMETRICAL OBSERVATIONS.

Seismometric observation was the branch of seismology that Milne cultivated with more zeal and mastery than any other, and which he most improved. This is the more noteworthy when we remember the crudeness of the instruments used before 1880, when they lacked proper foundation, construction and mass. A large part of present day seismometry is the result of his experiments and inventions, and we owe to his persistent efforts one of the best seismographs, "the Milne horizontal pendulum," now used all over the world. It is unnecessary to go into details here regarding the numerous papers published by Milne on this very important subject. The list of the seismological observatories in which the Milne horizontal pendulum is employed demonstrates its usefulness. There are now fifty-nine such observatories, and on account of their homogeneity the seismometrical observations recorded by them are of the greatest value. A great many of these Milne pendulums have been established under the auspices of the British Association for the Advancement of Science, or at its cost, but in every instance always by Milne's initiative.

LIST OF STATIONS WITH MILNE PENDULUMS.

Shide Hill House, Kew, Haslemere, Guilford, West Bromwich, Bidston, Stonyhurst, Eskdalemuir, Paisley, Edinburgh, Cardiff, Cork, Paris, Strassburg, Coimbra, San Fernando, Rio Tinto, Ponta Delgada, Malta, Cairo, Beyruth, Tiflis, Seychelles, Mauritius, Cape Town, Accra, Cape Verde, Fernando de Noronha, Ascension, St. Helena, Chacarita, Pilar, Lima, Trinidad, Mexico, Bermuda, Baltimore, Philadelphia, Toronto, Victoria, B. C., Honolulu, Fanning Island, Tokyo, Irkutsk, Taschkent, Calcutta, Vizagapatam, Bombay, Kodiakanal, Colombo, Batavia, Cocos, Keeling Islands, Perth, Adelaide, Melbourne, Sidney, Wellington, Christchurch, Fiji.

The seismometrical observations of these fifty-nine stations were brought together at Shide Hill House laboratory. Never had a geophysicist been the chief or leader of such an extensive, or rather such a world-wide net-work of geophysical observations, and Milne must ever remain one of the wisest and most ingenious founders of modern seismometry.

29. "Experiments in observational seismology." *T. S. S. Japan*, 1881, **3**, 12.

In this memoir Milne says:

> This paper may be regarded as being to a great extent the history of a series of investigations which led to the use of the instruments which I now employ for recording and measuring earthquakes.

30. "Earthquake observations and experiments in Japan." Milne and T. Gray, *Philosophical Magazine*, November 1881.

31. "On seismic experiments." Milne and T. Gray. *Proceedings of the Royal Society of London*, 1882, No. 217.

32. "Modern forms of pendulum seismometers." *T. S. S. Japan*, 1888, **12**, 22.

In these are given descriptions and the theory of the double Milne-Ewing pendulum.

33. "The Gray-Milne seismograph and other instruments in the seismological laboratory of the Imperial College of Engineering." *T. S. S. Japan*, 1888, **12**, 33.

This paper is but the reproduction, with additional notes, of a memoir published by Gray on this seismograph. *Philosophical Magazine*, April 1887.

34. "Instructions for setting up the Gray-Milne seismograph." *T. S. S. Japan,* 1888, **12,** 49.

35. "Diagrams of earthquakes recorded at the Chiri-Kioku (meteorological department) in Tokyo." *T. S. S. Japan,* 1890, **15,** 93.

36. "A mantelpiece seismometer." *T. S. S. Japan,* 1892, **16,** 47.

37. "Report of the Chiri-Kioku in Tokyo on seismometrical observations made in Japan during the year 1888." (Epitomized.) *T. S. S. Japan,* 1892, **16,** 55.

38. "Seismometrical observations for the year 1890." *S. J. Japan,* **1**; *T. S. S. Japan,* 1893, **17,** 31.

39. "On the movements of horizontal pendulums." *S. J. Japan,* **1**; *T. S. S. Japan,* 1893, **17,** 113.

40. "A note on horizontal pendulums." *S. J. Japan,* **3**; *T. S. S. Japan,* 1894, **19,** 55.

In addition to these memoirs, Milne has published a great number of brief notes on the same subject in the reports of the British Association for the Advancement of Science.

V. SEISMIC MOVEMENT.

Although Milne has investigated almost all the aspects of seismic problems, it is clear from a careful study of his entire work and from the chronological development or advance of his experiments or observations, that his chief aim was to study and discover the geometrical properties or modalities of seismic motion; so that a great part of our present knowledge of this movement we owe to his labor. It is noticeable also that he preferred always experimental methods to the mathematical or theoretical ones. He was the first seismologist to announce that an earthquake can put in vibration the entire terrestrial mass, a very important discovery that was demonstrated afterwards by his own experiments and by those of von Rebeur-Paschwitz.

41. "Notes on the horizontal and vertical motion of the earthquake of March 8, 1881." *T. S. S. Japan,* 1881, **3,** 129.

42. "Earthquake motion." *The Chrysanthemum,* 1882.

43. "Earth movement." *The Times,* October 11, 1882.

44. "Seismic experiments." *T. S. S. Japan,* 1885, **8,** 1.

In this paper Milne describes the experiment by means of which he improved the seismographic instruments for the purpose of discovering the forms of earthquake motion.

45. "The character of earth-waves near their origin." Third *R. S. I.*, 1898, 218.

In this he deals with a detailed analysis of the phases of seismograms.

46. "Apparent velocity of preliminary tremors." Fourth *R. S. I.*, 1899, 34.

47. "Earthquake echoes." *Idem*, 67.

VI. EARTH TREMORS AND PULSATIONS

If Milne did not anticipate the Italian seismologists Bertelli, de Rossi, and others in the discovery of the earth's minute movements as tremors and pulsations, he has at least investigated them with more precision than any one else. But considering that these geophysical phenomena lie beyond the seismic spectrum or gamut, as the bradyseisms also, we shall quote only the principal papers that Milne has published on this very interesting phase of geophysics.

48. "Earth pulsations." *T. S. S. Japan*, January-June 1883, **6**, 1.

49. "Earth tremors." *T. S. S. Japan*, 1883-84, **7**, Part I, 1.

50. "Earth tremors." *Nature*, **19**, 290.

51. "Earth tremors in central Japan recorded by an automatic tremor measurer." *T. S. S. Japan*, 1887, **11**, 1.

Milne concludes this paper with the following remarks:

> So far as my observations have hitherto gone in Japan, it appears that the majority of earth tremors are movements produced by the action of the wind upon the surface of the earth, and that these may often be propagated to distant places where wind disturbances have not occurred.

Later on Milne greatly amplified this rather narrow view of these minute movements of the terrestial crust.

52. "Earth tremors in central Japan." *T. S. S. Japan*, 1889, **13**, Part 1, 7.

53. "Tremors and pulsations; their relationship to the hours of the day." First *R. S. I.*, 1896, 20.

We ought to point out an interesting fact. The hourly diagrams of frequency and intensities of the tremors observed by Milne during November and December 1895 show a maximum close to XIX*h* and a minimum close to VI*h;* from which he concluded that there is some influence, external to the terrestrial crust, that is more active during the day than during the night.

VII. GEOGRAPHICAL AND GEOLOGICAL POINTS OF VIEW

Although Milne did not enter into the details of the geological aspects of earthquakes, he has obtained in seismical geography some results of the greatest value, the geological importance of which scarcely begins to be fully understood even now.

54. "The distribution of seismic activity in Japan." *T. S. S. Japan,* January-June 1882, **4,** 1.

55. "On a seismic survey made in Tokyo in 1884 and 1885." *T. S. S. Japan,* 1887, **10,** 1.

It is easy to conceive of the great practical interest that people have in a great city in regard to dangers that threaten their buildings. Milne met this matter for Tokyo either by means of direct observations or by setting up temporarily seismographs in many parts of the city; and he returned again to the same subject in the following paper.

56. "On the distribution of earthquake motion within a small area." *T. S. S. Japan,* 1889, **13,** Part I, 41.

57. "Movements of the earth's crust." *Geographical Journal,* March 1896.

58. "Suboceanic changes." *Geographical Journal,* August and September 1897.

59. "Suboceanic changes." Third *R. S. I.,* 1896, 251.

Milne has often investigated the difficult problem of the breaking of submarine cables and of determining whether these breaks are or are not due to seismic disturbances. With this aim he has published in the paper above quoted a list of eighty-five such ruptures which he compared with a parallel list of unfelt earthquakes. Except in a few cases the times of the phenomena do not coincide, even with a very rough approximation, so that the question remains as yet unsolved. However, we ought to quote Milne's conclusion:

> Off the coast lines there is a tendency for sediments and detritus derived from the land, accumulating under the influence of gravity, to assume unstable contours. That such contours had an existence is shown by reference to soundings. By excessive deposition of sediments, the suboceanic escape of waters from subterranean sources, the sudden release of waters backed up in bays by gales, changes in the magnitude and direction of ocean currents, and by suboceanic seismic and volcanic action, sudden and extensive yieldings may take place along the faces of slopes in a critical condition. That such suboceanic landslides had often taken place was proven by an appeal to the experience of

cable engineers, who often found that cable interruptions were the result of this burial along lengths of several miles, the materials covering the lost sections having fallen from the faces of slopes along the base of which the cables had been laid. In a few instances it was noted that there had been a considerable increase in the depth of the ocean along a line of slip. Many examples were given where cable interruptions accompanied an earthquake which had a submarine origin, and therefore it may be presumed that it was the earthquake which caused the landslip beneath the ocean, in the same manner that severe earthquakes result in similar displacements of what are probably much more stable surfaces on the land.

From 1900 to 1912 Milne brought together annually, and set down on maps of the world, the epicenters of the more important earthquakes, whether felt or instrumentally registered at his own observatory at Shide Hill House or at the stations established by the British Association all around the globe, the list of which is given above. In 1900 he published his first note and map of the world on this subject, and expounded at this epoch four methods for calculating the geographical coordinates of an epicenter by means of the diverse data furnished by a seismogram.

60. "The origins of large earthquakes which were recorded in the Isle of Wight in the year 1900." Fifth *R. S. I.*, 1900, 80.

61. "The origins of the earthquakes recorded in 1899, 1900, and 1901." Seventh *R. S. I.*, 1902, 3.

62. "The origins of large earthquakes recorded in 1902 and since 1899." Eighth *R. S. I.*, 1903, 2.

Later we shall return to the geographical seismic distribution obtained by Milne, the results of which he has collected in the following memoir with very interesting comments.

63. "Seismological observations and earth physics." *Geographical Journal,* January 1903, London.

Afterwards he uninterruptedly pursued his task up to 1904.

64. "The origins of large earthquakes, 1899-1903." Ninth *R. S. I.*, 1904, 3.

65. "*Idem,* 1899-1904." Tenth *R. S. I.*, 1905, 9.

66. "*Idem,* 1899-1906." Twelfth *R. S. I.*, 1907, 3.

67. "*Idem,* 1899-1907." Thirteenth *R. S. I.*, 1908, 3.

68. "*Idem,* 1899-1908." Fourteenth *R. S. I.*, 1909, 5.

In all these annual seismic world-maps Milne included the calculated epicenters in ovals more or less extensive, which, saving only one exception, the Mediterranean or Alpin-Himalayan oval, are situated in the oceanic areas,—indeed not far from the coasts. These results, or this geographical distribution of earthquake activity, have obtained little acceptance, especially in regard to geographical investigations in which other seismologists had employed only direct observations of earthquakes, and had pointed the epicenters on world-maps without taking into account the seismographical registrations of felt or unfelt seismic disturbances. In his paper on the earthquakes of 1909 Milne changed his mode of graphical representation, so that his new earthquake world-map has been greatly improved.

69. "Distribution of earthquakes in 1909." Fifteenth *R. S. I.*, 1910, 4.

In this last seismic world-map there are not more ovals for each cluster or group of epicenters, and Milne marked out only their axes; so that we now have to deal with seismic tracts of linear form, some of which have geological significance,—for instance, the submerged geoanticlinal of the middle Atlantic. These seismic lines do not differ much from the more important lines of terrestrial relief, or lines of corrugation of the crust, wrinkles, or furrows, emerged or submerged. The two following papers that Milne published on this subject are more important still.

70. "Seismic activity, 1899 to 1903." Sixteenth *R. S. I.*, 1911, 26.

71. "Seismic activity, 1904 to 1909." Seventeenth *R. S. I.*, 1912, 4.

In both papers before mentioned, and also in many others, Milne gives the name of *megaseisms* to the earthquakes which have been recorded in all the seismological observatories of the world, or in those which correspond to an area not less than that of two continents. In the former instances they are more or less destructive earthquakes, while in the latter cases they are unfelt teleseisms. On this occasion Milne has indicated their calculated epicenters on the world-maps, and we can verify by means of the accompanying lists that out of the 881 megaseismic disturbances only 311, or 35.3 per cent., have been felt, while the other 570, or 64.7 per cent., have not been observed on account of having originated off *terra firma* and too far from the coast.

If we combine the seismic world-maps of 1899-1903 and of 1904-1909, we see immediately that there is no direct contradiction between the geographical distribution of earthquake epicenters obtained by Milne and those determined by direct observations of earthquakes felt on land. These methods supplement each other in such a way that we are able to deduce from them a new fact, that Milne had not had time to expound, which is, that the laws of geographical distribution of megaseisms are identically the same on land and beneath the ocean as regards the seismogenic influence of the relief and of the recent revolutions in earlier geologic eras. This very noticeable point of view comes from the later investigations published by Milne, but, as we think, it would be somewhat premature to state here fully the deductions from Milne's geographical labors.

VIII. Relationship Between Seisms and Other Phenomena of Earth Physics

It is well known how many matters of importance there are in seismological literature relating to the old but not yet settled problem of the relationship which many people think exists between the seismic disturbances and other phenomena of earth physics. Milne has often investigated the subject with all his usual precision and impartial perspicacity.

72. "Earthquakes in connection with electric and magnetic phenomena." *T. S. S. Japan,* 1890, **15,** 135.

This paper is only a catalogue of observations of the class above alluded to, for Milne makes no study of the problem.

73. "Earth pulsations and mine gas." *Transactions of the Federated Institute of Mining Engineers,* June 1893, **5.**

74. "A note on earth pulsations and mine gas." *S. J. Japan,* **3**; *T. S. S. Japan,* 1894, **19,** 65.

Admitting that there can be relationship between the escape of gas or explosions in certain collieries and certain undulating motions of the earth crust, Milne suggests that Chesneau's observations and experiments be repeated.

75. "Earth pulsations in relation to certain natural phenomena and physical investigations." *S. J. Japan,* **1**; *T. S. S. Japan,* 1893, **17,** 87.

76. "Seismic, magnetic and electric phenomena." *S. J. Japan,* **3**; *T. S. S. Japan,* 1894, **19,** 23.

Milne's conclusions on this very controverted subject should be quoted.

> Although in this and other papers I have brought together a considerable number of observations that would lead us to believe that there might be a con-

> nection between earthquakes and magnetic and electric phenomena; that hypotheses have been formulated to assist in the conception of the possibility of such connection; that a variety of experiments and investigations have been made to test whether earthquakes were preceded, accompanied, or followed by magnetic or electric phenomena: the results obtained do not guarantee the existence of such connections.
>
> It does not seem likely that earthquakes can result from electric discharges, and it has not yet been proved that they give rise to electric phenomena. When they have resulted in the displacement of large masses of rocky strata, as happened in 1891 in central Japan, slight local changes in magnetic curves have resulted; but beyond this and effects due to the mechanical shaking of earth plates, our certain knowledge is exceedingly small.

All this is equivalent to a negation as regards such a relationship.

77. "On certain disturbances in the records of magnetometers and the occurrence of earthquakes." Third *R. S. I.*, 1898, 226.

From this extensive catalogue of observations and after having examined many magnetograms that he reproduces in this paper, Milne concludes as follows:

> Although we are aware that the records from certain magnetic observatories rarely, and then only slightly, show that the magnetographs have been disturbed at or about the time of large earthquakes, it is certain that at other observatories these movements of the ground are accompanied and possibly preceded by perturbations, as shown upon magnetograms, of a very marked character. In some instances these disturbances have evidently resulted from the mechanical shaking to which the magnetic needles have been subjected, but there are other cases where such an explanation is not so clear.
>
> The large sudden subterranean adjustments may not occur on the average more than twenty times per year; but if we attribute the smaller earthquakes to similar activities, these may, on the average, take place every half hour; and although none of these latter is likely to produce an appreciable magnetic effect on the surface of our earth, their cumulative effect after a sufficient interval of time, as representing a rearrangement and new condition of magnetic material, might possibly result in measurable changes in magnetic elements.

78. "Earthquakes and rain." Fifth *R. S. I.*, 1900, 106.

Milne often tried to find out whether earthquakes show any relationship with such meteorological disturbances as rain, and in a paper already mentioned (72) he states that in Japan in particular districts when comparing the annual curves of seismic intensity and those of rainfall, earthquakes have been frequent during the rainy seasons of certain years, while during other years they were rare in the same seasons. He returned to the problem in the paper last quoted, the final conclusions of which are as follows:

In considering whether there is any possibility of a connection between the phenomena here considered we must remember that observations showing that rain and cloud have followed closely on the heels of certain earthquakes (Mexico, January 24, 1898; Assam, June 12, 1897) appeared to be confined to tropical and semitropical countries; and it is in these countries where sudden showers, indicating the collapse of critical atmospheric conditions, are frequent. Given, therefore, such conditions at no great distance above the surface of the earth—which was probably the condition in the highlands of Assam—and then admit that beneath the gaseous covering, consisting of layers of air of different temperatures and with different degrees of saturation, 10,000 square miles of mountainous country was moved, or that a much larger area was thrown into violent wave-like movement, we recognize that the relationship of earthquakes and rain may not be improbable, as is generally supposed. As the ground rose upwards, the air immediately above it would suffer compression, and as the ground fell there would be rarefaction, whilst layers of air differing in their physical state might be mixed, and a vigorous seismic activity might in this way result in precipitation.

IX. Aseismic Buildings. Practical Seismology.

Being both an engineer and a seismologist, Milne could not overlook the problem of aseismic buildings. He therefore published many papers and some important memoirs on this subject, which he often had the opportunity of investigating by means of direct observations on the destructive effects of the numerous severe earthquakes he witnessed in Japan. To the study of earthquake-proof buildings he applied all of his perspicacity and clearness of mind, and we owe to him the invention and the use of a shaking table with which can be observed directly the effects of a shock similar to those of an earthquake on different materials of construction and on masses of different forms and sizes.

79. "Notes on the recent earthquakes of Yedo Plain, and their effects on certain buildings." *T. S. S. Japan,* July-December 1880, **2**, 1.

80. "Earthquakes and buildings." *Nature,* **19**, 290.

81. "Constructions in earthquake countries." *Proceedings Institute Civil Engineers,* 1885-86, **83**. Paper 2108.

82. "On construction in earthquake countries. With an abstract of the discussion upon the paper. Replies to the discussion." *T. S. S. Japan,* 1887, **11**, 14.

83. "Relative motion of neighboring points of ground." *T. S. S. Japan,* 1888, **12**, 63.

By means of seismometrical measurements Milne shows that neighboring points of ground or of a building can be given motions of unequal phases and amplitudes, so that their destruction is greatly facilitated and increased.

84. "The movement produced in certain buildings by earthquakes." *T. S. S. Japan,* 1888, **12,** 67.

85. "Building in earthquake countries." *Proceedings Institute Civil Engineers,* 1889-90, **100.**

86. "Construction in earthquake countries: a compilation, with a few original articles, respecting building in earthquake countries." An epitome of information useful to builders contained in the previous reports with remarks on the same. *T. S. S. Japan,* 1890, **14,** 23.

In this volume of the *Transactions of the Seismological Society of Japan* we have to deal with a true treatise on earthquake-proof buildings, that Milne has based on the experience acquired in all the seismic countries of the world.

87. "Construction in earthquake countries." A supplement to *T. S. S. Japan,* **14.** *T. S. S. Japan,* 1890, **15,** 163.

88. "On the mitigation of earthquake effects, and certain experiments in earth physics." *S. J. Japan,* **1**; *T. S. S. Japan,* 1893, **17,** 1.

89. "On the overturning and fracturing of brick and other columns by horizontally applied motion." Milne and Omori. *S. J. Japan,* **1**; *T. S. S. Japan,* 1893, **17,** 59.

Milne invented a special seismograph by means of which it is possible to investigate the state of conservation of the railways and of their locomotives, cars, tunnels and bridges. Since Milne's experiments this new branch of practical seismology has been greatly extended, especially in Japan, but in spite of its highly human importance, it has not been generally accepted in Europe for reasons that have no scientific bearing.

90. "Seismology as applied to railway trains." *T. S. S. Japan,* 1890, **15,** 23.

X. RELATIONSHIP BETWEEN EARTHQUAKES AND THE CHANGES OF THE VERTICAL AND OF LATITUDE.

Both of these problems have a geodetic and an astronomical aspect, and the first must be considered as not belonging to seismology, for the small variations of the vertical—that is to say, of the directions of gravity—do not seem to depend upon the earthquakes. They are movements of the terrestrial crust, but they attracted Milne's careful attention.

91. "Diurnal waves and wandering of the pendulum." First *R. S. I.*, 1896, 32.

Here Milne analyzes the observations made by him at Shide Hill House from May 24 to June 15, 1896, and confirmed fully those made at Strassburg from 1892 to 1894 by von Rebeur-Paschwitz on the movements of the "Null-Punkt." Besides a well proved diurnal oscillation, there is probably periodical variation which is directly related to the seasons and the months.

92. "Changes in the vertical observed in Tokyo, September 19, 1894, to March 1, 1896." First *R. S. I.*, 1896, 35.

From these observations it appears that in Tokyo changes in the vertical have occurred sometimes during certain earthquakes, but it is not clear from Milne's paper whether it is a matter of temporary changes or of variations of a more or less permanent character.

93. "Earthquakes and small changes in latitudes." Fifth *R. S. I.*, 1900, 107.

We cannot here inquire into the opinion according to which the epochs of frequent earthquakes, or megaseisms, are related to the maxima of the small periodical changes in latitude; but it is interesting to quote the conclusions at which Milne arrived in regard to the interdependence of these phenomena.

> Two points of importance are to be remembered when considering the possibility of any relationship between earthquakes and the extremely frequent and practically oscillatory changes in latitudes.
>
> The first is that in each of these earthquakes there is a sudden shifting of a large mass of material at a seismic origin. The molar displacement of the Indian earthquake of June 12, 1897, is estimated by R. D. Oldham by an area of 6000 or 7000 square miles, and it is not improbable that earthquakes which caused the Pacific ocean to oscillate for a period of twenty-four hours were accompanied by displacements of larger magnitude.
>
> The second consideration is that each of the large earthquakes here considered has been accompanied by surface or distortional waves, which in many instances affect the whole surface of the globe. These waves, so far as we can infer from their velocity, period, and maximum angle of inclination, vary between twenty and seventy miles in length, and are from a few inches to two or three feet in height. If they attain the magnitudes here given they seem certainly sufficient to relieve a district in orogenic strain.

This latter phrase seems to signify that, according to Milne's opinion, the passage of seismic waves, perhaps even if they were unfelt, could give rise to orogenic earthquakes; and in this same paper Milne repeats one of his earlier assertions,[4] to the effect that the periods of maxima of latitudes in Berlin coincide apparently with the maxima of earthquake frequency in Japan.

94. "Large earthquakes and small changes in latitudes." Eighth *R. S. I.*, 1903, 2.

Here Milne has drawn a parallel between Albrecht's diagrams of changes in latitudes, observed from 1891 to 1901, and the annual numbers of megaseisms.

XI. VOLCANOES.

Milne has published several papers upon volcanic subjects, and he has insisted many times on the independence of volcanic and seismic phenomena, which is now a generally accepted opinion. This fact is of the greatest importance in theoretical geology, so that we must remember the more explicit texts in which he defended this point of view with reference to articles before quoted.

> The central portion of Japan, where are the mountainous districts where active volcanoes are numerous, is singularly free from earthquakes. (20.)
>
> In Japan, the majority of the earthquakes which we experienced do not come from volcanoes, nor do they seem to have any direct connection with them. (27.)
>
> Even in volcanic countries, the majority of earthquakes which are recorded do not appear to be in any way connected with volcanic action. Before a volcano commences to erupt, there may be a few slight shakings of the ground, and there is certainly another effort, when the rocky material above the crater mouth is burst asunder. These occurrences are, however, rare; whilst earthquakes, many of which are large, are of continual occurrence; and whether a volcano is at rest or in a state of activity, these disturbances do not appear to be in any way affected. (89.)

95. "Report on earthquake observations made in Japan during the year 1889." *T. S. S. Japan*, 1890, **15**, 115.

Milne says:

> In short, in some places, though there are many volcanoes earthquakes seldom occur. In others, both earthquakes and volcanoes are few. And there are some places where there are volcanoes but the disturbances do not spread, and are limited to a particular spot.

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[4] *S. J. Japan*, 1897, **1**, 17.

Milne devoted himself to important and very valuable investigations upon the Japanese volcanoes.

96. "The volcanoes of Japan." *Japan Gazette,* December 31, 1881; April 15, 1882; September 20, 1882. Eight articles.

97. "The volcanoes of Japan." *T. S. S. Japan,* 1886, **9**, part II.

This volume of the *Transactions of the Seismological Society of Japan* was devoted by Milne entirely to accounts of the explorations he made of the very numerous Japanese volcanoes and to the original documents he could find in that country relating to their history or description. His work is nothing less than a full description of these volcanic mountains, either still active or extinguished. He illustrated his memoir with a great number of sketches made with his own hand, and he gives at the end the theoretical profile of a volcano. He also completed this general and valuable memoir by means of some more particular and detailed explorations made later.

98. "A visit to the volcano of Oshimo." *Geological Magazine,* Decade II, **5**, No. 8; **6**, No. 11, 193, 197, 255.

99. "On the form of volcanoes." *Idem* **5**, No. 8; **6**, No. 11.

100. "A cruise among the volcanoes of the Kurile Islands." *Idem* **6**, No. 8, 337.

From all this volcanological labor, let us remember that now the principle of the independence of volcanic and seismic phenomena has been based for some part upon the irrefutable observations that Milne made in Japan.

XII. INTERNAL HEAT AND STATE OF THE GLOBE. GEITE. ELASTICITY OF THE ROCKS.

The rather sensational discovery of modern seismology to the effect that the earth's core possesses a rigidity more than double that of the hardest steel, is based for the most part on Milne's experiments on earthquake-wave velocities. This has led to the abandonment of the old dogma of the fluidity or viscosity of the earth's core, although, according to the theories of Arrhenius and others, the results of recent seismometrical observations might be otherwise interpreted.

101. "The speed of earthquake motion and inferences based thereon relating to the interior of the world." Eighth *R. S. I.,* 1903, 7.

We reproduce here the very clear deductions that Milne has drawn from his own observations.

> The high values of 10.5 to 12 km. per second (preliminary tremors) suggest a high velocity for the world, whilst the approximate uniformity of speed within its core indicates approximate uniformity in those properties which determine the rate at which it transmits vibrations. Unless it is assumed that as we descend in the earth elasticity and density increase in the same ratio, to which hypothesis there are objections, the inference is that the nucleus of the world has a density more nearly uniform than is generally assumed.
>
> To satisfy the interpretation given to these seismometrical observations, what is required is a globe with an approximately uniform nucleus not less than 19/20 of the earth's radius, covered by a shell which passes rapidly upwards into the materials which constitute the crust of the world.
>
> That low velocities are found on wave paths corresponding to chords of less than 10° suggests that this crust is not more than forty miles in thickness. . . . What the velocity table [as it now stands (the table of this paper)] indicates is that a crust passes rapidly into a nucleus which is exceedingly rigid and fairly homogeneous. A specific gravity can be defined for this nucleus which will meet the requirements of gravitational observations, and it seems likely that the same may accord with the tests of the astronomer.

It is to this intermediary zone between the external crust (1/20 of the radius), and the internal core (19/20 of the radius), that Milne has given the name of "Geite," a subject to which he often reverts.

102. "Seismometry and Geite." *Nature,* April 9, 1903, 538. Die Erdbebenforschung und die Singeweide Erde. Die Erdbebenwarte III, Layback, 1903-04, 6.

103. "Utilization of the earth's internal heat. A discussion opened by J. Milne." *T. S. S. Japan,* January to June 1882, 4, 61.

104. "Note on the cooling of the earth." *Geological Magazine,* Decade II, 7, No. III, 99.

The determination of the coefficients of elasticity of rocks has been of great importance in seismometrical investigation, for they influence directly the speed of propagation of the different earthquake waves, and perhaps the production itself of seismic phenomena. In 1882 Milne attacked this very delicate problem, which from that date has given way to very important experiments and theories.

105. "On the elasticity and strength constants of certain rocks." *Quarterly Journal of the Geological Society,* 1882.

XIII. SEISMOLOGICAL MISCELLANEA

Under this head we may mention special papers which show that Milne neglected none of the multiple aspects of seismic phenomena.

106. "Note on the sound phenomena of earthquakes." *T. S. S. Japan,* 1888, **12,** 53.

In this paper Milne calls attention to the "Retumbos," and argues from the observations made and the theories expounded.

107. "On the synchronism of seismic activity in different districts." Sixteenth *R. S. I.,* 1911, 7.

From his catalogue of destructive earthquakes (21), Milne concluded that periods of great seismic activity in certain districts correspond to periods of relative seismic rest in certain others, which is a mode of stating the constancy of the seismic activity of the globe, at least if we consider periods of sufficient duration.

108. "On a new periodicity in earthquake frequency." Seventeenth *R. S. I.,* 1912, 27.

From the same catalogue Milne has deduced that the megaseisms do group themselves in clusters, which are separated by poorer periods of fifteen and thirty days approximately, so that if the globe is considered as a whole, the seismic strain should be relieved every fifteen or thirty days by large earthquakes.

109. "Catachtonic observatory in Japan." *Nature,* **19,** 413.

110. "Earthquake effects, emotional and moral." *T. S. S. Japan,* 1887, **11,** 91.

This very interesting and curious paper has an historic and philosophical value as regards earthquake effects on the mind of men and on the religious sentiments and superstitions that have originated in remote centuries.

111. "Note on the effects produced by earthquakes upon the lower animals." *T. S. S. Japan,* 1888, **12,** 1.

According to Milne's observations and opinion it seems that animals feel the preliminary tremors of an earthquake, although they are not gifted with any seismic foresight, as has often been assumed by inconsiderate observers.

XIV. Bibliography and Biography

Although it is not easy to compile the entire bibliography of Milne's seismological labors, we are confident that none of his important papers has escaped us. He has published two incomplete bibliographical lists, one as an "Appendix to seismology," p. 312, and another in:

112. "Recent publications chiefly referring to seismic and volcanic phenomena in Japan." *T. S. S. Japan,* 1883-84, 7, 89.

The only biographical sketch of the late master we know of is that published by Mrs. Lou Henry Hoover, entitled "John Milne, Seismologist," and published in the *Bulletin of the Seismological Society of America,* March 1912, 2, 2. Stanford University, California.

NOTES ON THE SAN BRUNO EARTHQUAKE OF JANUARY 23, 1914

By E. F. Davis

Though this was only a feeble shock, its intensity in the region of San Francisco Bay was probably greater than that of any earthquake since that of July 1, 1911. The earthquake was well recorded at Berkeley by the instruments at the University of California Seismographic Station, and at Santa Clara by the University of Santa Clara Station. The record at the Lick Observatory Station was not very good, but a fairly accurate determination of the time of duration of the preliminary tremors could be made.

At Berkeley, the earthquake was generally felt and had an intensity of III to IV of the Rossi-Forel scale. Its intensity was not great enough to start the Marvin Seismograph. Some differences were noted in the reports of those who felt the earthquake: The majority of those reporting the earthquake stated that they felt two maximum movements, separated by a short interval of time. Other careful observers stated that they felt only a single strong movement. The horizontal records at Berkeley showed two maxima, separated by an interval of about a second and a half. The vertical record, however, showed only a single maximum. Many observers reported that the movement was strongest in the north-south component, while the seismographic records indicated the east-west component of motion to be the greatest. The amplitudes of the first and second maxima at Berkeley were as follows:

	First	Second
East-West	235 microns	248 microns
North-South	69 "	123 "
Vertical	29 "	

The periods in all cases were approximately half a second.

In San Francisco, the intensity of the earthquake was considerably higher than at Berkeley, being IV to V of the Rossi-Forel scale.

At the Lick Observatory the earthquake was not reported as being felt. At Santa Clara a slight shock was felt. At Clayton the earthquake was barely perceptible. At Livermore it was felt by only a few persons who were favorably situated. At San Gregorio, which lies on the coast near Purissima, the earthquake was more severe than it was in Berkeley, and apparently the intensity here was about as great as it was in San Francisco.

The following are the times of duration of the preliminary tremors as determined from the seismograms at the three stations mentioned above:

Lick Observatory	9.8	seconds
Santa Clara	6.9	"
Berkeley	4.1	"

In reducing these values and determining the epicentral distance from each station, Omori's formula for local shocks was used. This is,

$$x^{km} = 6.86y^{sec} + 8.1^{km}$$

The epicentral distances obtained in this way are as follows:

Lick Observatory	75.4	km.	46.8	miles
Santa Clara	55.5	"	34.4	"
Berkeley	36.3	"	22.5	"

The direction of the epicenter could not be determined at either the Lick or Berkeley stations on account of the rapid period of the first preliminary tremors. At Santa Clara the records showed that the epicenter lay to the northwest of the station.

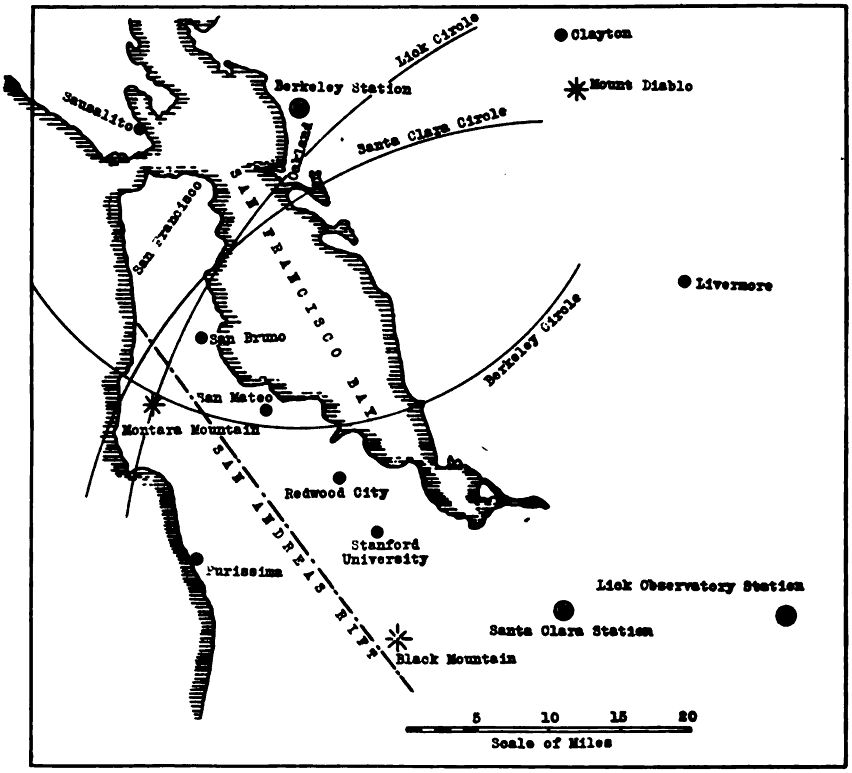
Three circles were constructed with radii equal to the foregoing values of epicentral distance, and with their centers at the respective stations, as indicated in the accompanying figure. These three circles intersect in the neighborhood of San Bruno, and the center of gravity of the resulting triangle lies very nearly on the San Andreas Rift at a point north of Montara Mountain and west of San Bruno.

With regard to the time of occurrence, at the origin of this earthquake, it is apparent that this can readily be approximated. The time of arrival at both Lick and Berkeley stations is known within half a second. The first movement of the pens on the Berkeley records occured at 7h 32m 48.5s p.m. (Pacific Standard Time). The first movement at Lick occurred at 7h 32m 54.1s p.m. The epicentral distance from each station is approximately known. The velocity of propagation of the first phase may be assumed as seven kilometers per second. On these assumptions one will obtain the following values for the time of occurrence:

7h 32m 43s.4 (from Lick records)
7h 32m 43s.3 (from Berkeley records)

The time of occurrence may then be given as 7h 32m 43s ± p.m. (Pacific Standard Time).

It is interesting to note that this particular shock is the third earthquake known certainly to have originated on the San Andreas Rift, in the vicinity of San Francisco, within the last few months.



Earthquake of January 23, 1914.

On September 12, 1912, an earthquake occurred which had its origin on the San Andreas Rift just north of Santa Cruz in the neighborhood of Black Mountain.

On October 25, 1913, an earthquake occurred which had its origin on the San Andreas Rift northwest of Berkeley. The exact position of the epicenter could not be determined.

In conclusion the writer would make mention of his obligation to the Reverend J. S. Ricard, of the University of Santa Clara, for his kindness in furnishing measurements of his records, and for information as to the intensity of the earthquake in Santa Clara.

UNIVERSITY OF CALIFORNIA.

CONCERNING THE PERCEPTIBILITY OF WEAK EARTHQUAKES AND THEIR DYNAMICAL MEASUREMENT

By Harry O. Wood

For defining the *intensity of an earthquake* it is a general practice to assume this quantity to be proportional to the acceleration of the vibratory motion of the disturbed earth-particles. Such was the measure of intensity employed by Professor E. S. Holden in his study of California earthquakes; values of acceleration are used by Omori in fixing the limits of the arbitrary grades of his "absolute" scale of intensity; by Cancani in systematically dividing the intensity range into grades in his dynamic scale; and very recently by Galitzin, referring to the overthrow of standing parallelepipeds of fixed height and cross-section, thus determining values of acceleration as dynamic measures of intensity. Also Dutton, in the text of his "Earthquakes," speaks of intensity as proportional to acceleration, but when he comes to state a mathematical equivalent for it he gives the following formula, indicative of the "rate at which energy is transmitted across unit area of a plane parallel to the wave front,"

$$I = \frac{2\pi^2 a^2 VD}{t^2}$$

in which

$I =$ the intensity,
$V =$ the velocity of wave transmission,
$D =$ the density of the medium,
$a =$ the amplitude of vibration of the earth-particle,
$t =$ the period of vibration of the earth-particle,

The acceleration is given as

$$a = \frac{4\pi^2 a}{t^2};$$

whence, therefore,

$$I = \frac{4\pi^2 a}{t^2} a \frac{VD}{2} = kaa,$$

in which $k = \frac{VD}{2}$ is a constant.

This expression makes the intensity ***proportional to the amplitude explicitly,*** as well as implicitly in the acceleration, as the writer has heretofore pointed out. This seems a point of importance, because even with very small amplitudes, very high values of acceleration result when the period of vibration is very small. But with very small amplitudes, even when the period is very short, it would seem improbable that perceptibly high intensity is developed, and the following discussion helps to show this.

The minimum perceptible unit of seismic intensity has never been determined by psychological experimentation, so far as the writer is aware. However, in his study of earthquakes in California, Professor E. S. Holden wrote:

" . . . I have found twenty shocks, ranging in intensity from I to IX (R-F scale), in which the amplitudes and periods were determined by instruments, and in which I could assign the Rossi-Forel intensity with confidence. The following table is the result:

Equivalents of the degree of intensity of earthquake shocks on the Rossi-Forel scale in terms of the acceleration due to the velocity of the shock itself.

Degree R-F Scale	Intensity	Difference
1 corresponds to	20 mm. per sec. per sec.	—
2 corresponds to	40 mm. per sec. per sec.	20

. . . .

Holden does not state whether these are maximum or mean values for the grades. In any case, however, these equivalents, though dependent upon instrumental measures, were not determined in a precise physical way. But they must be approximate and, therefore, of service. By definition, Grade I is "felt by an experienced observer." Hence, according to Holden, the minimum perceptible unit, measured by acceleration, must correspond to a value less than 20 mm. per sec. per sec.

Cancani, in proposing a regularly divided, dynamic scale of intensity, designated by the term "sensible" the fourth grade, comprising a range of acceleration beginning with 10 mm. per sec. per sec. and ending with 25 mm. per sec. per sec. The inference is clear that shocks whose acceleration values fall below 10 mm. per sec. per sec. he did not consider perceptible to the senses. To what extent his estimate was based upon experiment is not known to the present writer. However, though precision probably can not be claimed for this procedure, as a working hypothesis it is legitimate and expedient to adopt this estimate, 10 mm. per sec. per sec., as the ***minimum acceleration-value of seismic intensity perceptible to the senses.*** While this value may prove too low for some observers, experience gained in connection with the after-shocks of the 1906 earthquake in California leads me to the opinion that, if Holden's R-F estimates for California shocks are fairly well judged, very many sensitive observers can detect vibrations of about the value assumed as minimum. Therefore, in standard seismometric notation, following Angenheister,

10 mm. per sec. per sec. = 10,000 μ per sec. per sec. = 1,000 milligals

is provisionally the minimum perceptible acceleration-measure of seismic intensity.

In the Whitney Laboratory of Seismology at the Hawaiian Volcano Observatory, the installation of a complete, two component Bosch-Omori 100-kg. tromometer was completed about the middle of May, 1913, when routine registration with these instruments was begun. At the same time registration was resumed with the single-component, heavy Omori tromometer which had been in use previously. These instruments were adjusted to have the following constants, which so far as possible have been maintained by slight adjustments from time to time:

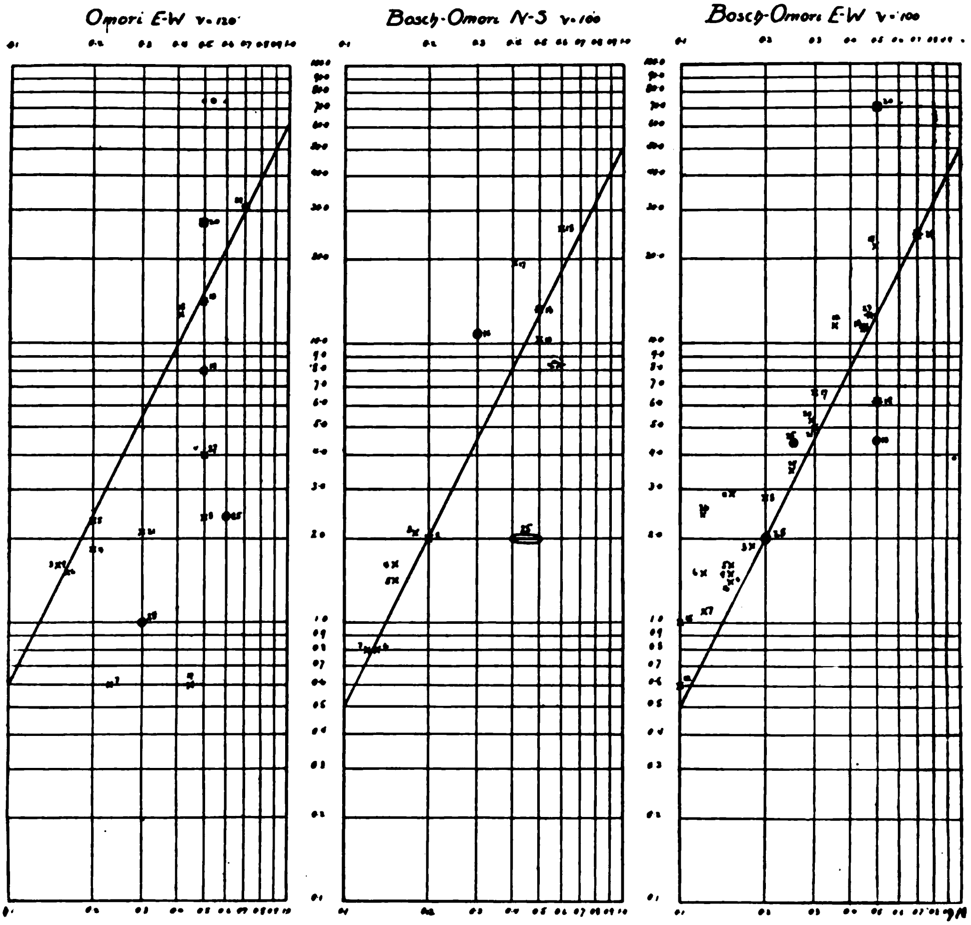
Bosch-Omori E-W, $V = 100$, $T_0 = 15$ sec., $E = 8:1$
Bosch-Omori N-S, $V = 100$, $T_0 = 15$ sec., $E = 8:1$
Omori E-W, $V = 120$, $T_0 = 15$ sec., $E = 1.2:1$

From the middle of May, 1913, until the end of the year, twenty-nine moderate to moderately strong earthquakes, *instrumentally considered*, were registered. Most of these require our attention in this discussion of intensity. For with one or two exceptions they were very feeble, or imperceptible, to the senses. They are assembled in the following table which, for each component, gives dates, double-amplitudes directly measured in millimeters, single amplitudes reduced to microns, periods in fractions of a second, and calculated acceleration values for the maximal phases of the shocks: also statements as to whether the shocks were felt or not felt, at this place or in its immediate vicinity.

Omori E-W				Bosch-Omori N-S				Bosch-Omori E-W				Date				Remarks
A μ	2A mm	T	a	A μ	2A mm	T	a	A μ	2A mm	T	a	1913				
												May	19	1		Felt generally IV R-F
												June	8	2		Felt generally II-III R-F
7.0	1.6	(?)0.15	1200	10.5	2.1	0.18	1300	9.5	1.9	0.18	1200	"	18	3	×	Not felt
7.5	1.8	(?)0.2	910+	8.0	1.6	0.15	1400	7.0	1.4	0.15	1200	"	19	4	×	" "
10.0	2.3	0.2	960	7.0	1.4	0.15	1200	8.0	1.6	0.15	1400	"	19	5	×	" "
6.5	1.5	0.16	980	4.0	0.8	0.13	950	7.5	1.5	0.12	2100	"	21	6	×	" "
2.5	0.6	0.23	190	4.0	0.8	0.12	1100	5.5	1.1	0.12	1500	"	25	7	×	" "
10.0	2.4	0.5	190	10.0	2.0	0.2	1000	14.0	2.8	0.2	1400	"	29	8	×	" "
7.0	1.6	(?)0.15	1300					7.5	1.5	0.15	1300	"	29	9	×	" "
				51.5	10.3	0.5	830	57.5	11.5	0.35	1900	July	1	10	×	" "
								14.5	2.9	0.15	2500	"	4	11	×	" "
								3.0	0.6	0.1	1200	"	7	12	×	" "
59.0	14.1	0.5	940	66.0	13.3	0.5	1070	57.0	11.4	0.45	1130	"	12	13	★	Felt at Kapa Pala but not at Volcano House
				54.0	10.7	0.3	2400	23.0	4.5	0.5	350	"	15	14	⊙	Not felt
								5.0	1.0	0.1	2000	"	29	15	×	" "
								7.0	1.4	0.15	1250	"	29	16	×	" "
25.0	6.0	0.4–0.5	500–750	97.0	19.4	0.4±	2400±	33.0	6.6	0.3±	1450±	Aug.	21	17	×	Not felt
55.0	12.6	0.4+	1200+	127.5	25.5	0.6	1400	110.0	22.0	0.5−	1700+	Sept.	20	18	×	" "
35.0	8.0	0.5	540					36.0	7.2	0.5	580	Oct.	2	19	★	Felt
115+	27+	0.5	1800+					350.0	70.0	0.5	5600	"	4	20	■	Felt generally
9.0	2.1	0.3	400					25.0	5.0	0.3	1100	"	8	21	×	Not felt
												"	25	22		Strongish weak-shock, VI R-F
								65.0	12.6	0.45–0.5	1200–1500	"	28	23	×	Not felt
								26.5	5.3	0.3−	1200+	Nov.	8	24	×	" "
10.0	2.4	0.6	110	10.0	2.0	0.4–0.5	160–250	22.0	4.4	0.25	1400	"	19	25	⊙	" "
								12.5	2.5	0.12	3500	"	29	26	×	" "
17.0	4.0	0.5	270					16.5	3.5	0.25	1100	Dec.	4	27	×	" "
4.0	1.0	0.3	185					10.0	2.0	0.2	1000	"	26	28	⊙	" "
130.0	30.6	0.7	1100					122	24.4	0.7	1000	"	26	29	★	Felt by one person lying down

The following symbols are also employed in this table and upon the accompanying diagram:

■ A shock universally felt in this neighborhood.
✱ Shocks judged to be of critical importance in this inquiry.
× Simply shocks instrumentally strong but not felt.
⊙ Shocks with important discrepancies as to certain magnitudes between different components.



There is hardly any doubt but that the acceleration-value reduced from measurement for all these shocks, but four, equalled or exceeded 1,000 milligals, the postulated minimum.

Of the four excepted, one, on October 2, 1913, was a shock distinctly perceptible to the senses, felt by several persons at the hotel near-by,—though its calculated acceleration, reduced from sufficiently accurate determinations of amplitude and period, is less than 600 milligals. This is very difficult to understand, since its motion was no quicker than, and of considerably less amount (about 1/3) than that of the shock on September 20th, which was not perceived by anyone hereabouts. No explanation is offered in this case. It stands as an anomaly.

The other three shocks, excepted above, present doubtful characteristics, in that low values of acceleration were developed in one or two components, while values equalling or exceeding 1,000 milligals are calculated from the seismogram in at least one component. Matters of interpretation in measurement may be responsible for the discrepancies in these cases. Exceptional amplitudes (or periods?) in a single direction may be the cause.

Therefore, putting aside the relatively strong shocks of May 19th, June 8th, October 4th and October 25th, which, save for completeness, really have no place in this tabulation, besides the three doubtful shocks mentioned already, there were registered *nineteen shocks not felt by any in this vicinity,* for which the reduced acceleration-values equal or exceed 1,000 milligals. Probably some of these would have been felt by a person reclining in perfect quiet and awake, particularly that on September 20th. However, all the buildings hereabouts are light, wooden-framed structures, mostly built in a flimsy way, and therefore well-adapted to draw attention to the occurrence of a slight earthquake. Hence it is not at all likely that all these shocks were perceptible, but were overlooked through the moving about, slumber, or inattention of all local residents.

Moreover, the shock of July 12th, ($\alpha = 1130$ milligals), felt at Kapapala (about sixteen miles southwest from the Hawaiian Volcano Observatory), but not felt in the immediate neighborhood of the Observatory; the shock of October 2d ($\alpha = 580$ milligals), already mentioned, felt generally at the Volcano House; and the shock of December 26th ($\alpha = 1100$-1000 milligals), felt at the Volcano House by a single person, lying down but thoroughly awake: these are critical shocks, so to speak; the circumstances of their occurrence greatly strengthen the view that the value, 1,000 milligals, was suitably chosen for the minimum perceptible unit—or, more strictly, that this value has not been fixed too low.

How, then, are we to account for the majority of these shocks, which were not sensibly perceived, but whose accelerations equalled or exceeded this reasonably chosen minimum limit?

The critical reader will perceive that in the case of the single-component Omori seismograph, the majority of these shocks wrote records whose reduction has yielded acceleration values less than 1,000 milligals, and from this fact he may infer that this is an instrument better adapted for the registration of shocks such as these, or that there are defects of design or construction in the Bosch-Omori pendulums responsible for the larger acceleration values. But such an inference could not be correct, nor, if it were, could it wholly resolve the difficulty: for (1) the Omori seismograph is practically undamped (so that there is the possibility of the quenching of vibrations by resonance), its frictional resistance is much greater than in the other two seismographs, and it is all the time proving less sensitive to microseisms, feeble local earthquakes and "volcanic vibrations"; moreover (2), having regard to this instrument alone, there occurred three shocks which were not perceived but whose acceleration-values measure in excess of 1,000 milligals. Hence we have not to do with exaggeration of the acceleration measures in the Bosch-Omori seismographs on account of instrumental peculiarities.

It will be noticed that the periods are very short—the longest being 0.7 second—and that they are stated to hundredths of seconds. Of course, no considerable precision is claimed for the hundredths digit, but the writer has adequate confidence in the order of magnitude of these quantities. Briefly, with the Bosch-Omori instruments the direct measure of the minute-interval has varied from 54 to 58, rarely 59 or 60, hundredths of an inch. And the number of *complete waves*, from crest to crest, has measured from three in a space of two hundredths of an inch, to twelve in a space of one hundredth of an inch. Reduction to fractions of seconds was made with the slide-rule.

Of course, slight errors in measurement of period would cause large errors in the reduced acceleration values. But in this study the general result would not be greatly changed, unless the periods have in all cases been determined too small. However, whatever error there is, is probably in the direction of measuring the period too long. For, with crowded waves, it is likely that too few were counted rather than too many. This means that the calculated accelerations are, if anything, too small rather than too large.

It may be suggested that the waves measured were compound, and that the periods of a small, rapid set have been combined with the amplitudes of a larger, slower set, thus exaggerating the acceleration. The writer has been on guard against such procedure, and considers that the waves measured were simple. At any rate, successive periods and amplitudes were of like order of magnitude, so far as ascertained.

Moreover, in computing the accelerations no correction for the frictional resistance at the writing point has been applied. Hence the amplitudes utilized were too small rather than too large, and so again with the resulting values of acceleration.

On the Bosch-Omori seismographs there was damping in the ratio of 8:1 approximately, and, besides this, the earth motion was very rapid relative to the proper period of the pendulums. Hence there is no likelihood that the motion was exaggerated by resonance.

Hence, in the judgment of the writer, we have to deal with a group of small earthquakes for which, in most cases, the acceleration of vibratory motion was genuinely in excess of 1,000 milligals.

On the accompanying diagram the acceleration-intensity of each of these shocks, for each component separately, is denoted by the position of its symbol and number—the same symbols and numbers as in the tabulation. The logarithmic net is employed because, with this method of platting, the curve of 1,000 milligals, referred to amplitudes and periods as co-ordinates, appears as a straight line. Ordinates represent double-amplitudes measured directly upon the seismogram in millimeters (and tenth-millimeters), and abscissae represent periods measured in tenth-seconds; the heavy oblique lines across the diagram for each component represent the curve of 1,000 milligals, above which rising to the left are higher and higher values, and below falling to the right lower and lower values. With both Bosch-Omori instruments the co-ordinates of the 1,000-milligal curve are the same, but slightly less than those for the Omori seismograph because of a small difference in the static magnifying power.

More of the shocks were well registered by the E-W Bosch-Omori seismograph than by either of the others. Consequently this discussion must be based largely upon this component.

It will be observed that only one shock had a period greater than 0.5 second, and that this shock was sensibly perceived, under favorable and critical conditions, with an acceleration of 1,000 milligals.

Four shocks had periods of 0.5 second; in one of these cases the acceleration-measure is doubtful; in a second case the shock was felt but stands as an anomaly; in a third case the shock was strong and was felt generally; and in the fourth case, No. 18, the acceleration was so high (in all components) that it is probable that the shock was perceptible, though unnoticed.

All the other shocks had periods less than 0.5 second, two as low as 0.1 second, and none of these shocks were felt in the near vicinity of the Observatory, although all developed accelerations above the line.

The diagram shows that *in a general way* some of the shocks of less and less period-length manifested greater and greater acceleration-values without rising into sensibility.

Too few of the shocks were well registered by the N-S Bosch-Omori seismograph—for tilting has frequently been so great as to throw its writing point off the recording cylinder—to afford any proper check, or verification, of the tendency noted in the E-W component. One shock, No. 14, in which the measure of acceleration is doubtful, would not tend to support it. Also the acceleration reached by No. 17 (period of 0.4 second) was higher than that reached by any other shock of shorter period in this component. The cases are too few, however, to warrant any conclusions.

In the N-S component there were only three shocks, one doubtfully measured, which fell below the line. Seven unfelt shocks whose periods were less than 0.5 are found above the line.

The obvious discrepancies presented by the diagram in the case of the Omori seismograph have been discussed above.

Such are the facts of the registration and measurement of these shocks, all of which had near-by origins. Using Zeissig's distance table, six of these shocks originated at distances of less than ten miles, six at distances of from twenty to thirty miles, and the remaining seventeen at distances of between ten and twenty miles. The rock in this region is porous and cavernous, and is traversed by many fissures of larger and smaller size.

While, therefore, there is too much in doubt, and too much discrepant, to warrant any settled conclusions, the writer thinks that the diagram for the Bosch-Omori E-W seismograph—which instrument has performed better than the others from an instrumental point of view—points suggestively to a relation of the following sort: that, for shocks to be sensibly perceptible, as the periods are smaller and smaller below, say, 0.5 second, the amplitudes must be larger and larger, increasing in a ratio greater than that required simply to bring the acceleration-value up to or slightly above 1,000 milligals. Or, in other words, that the amplitude is explicitly involved in the development of intensity (as well as implicitly through its role in the acceleration), as the formula given by Dutton requires; and further, that for this part of the range it may become the dominant factor.

This suggestion needs testing, both by the further study of actual shocks and, if possible, by experimentation. Though the writer feels that it is too early to declare a conclusion confidently, he sees nothing in the suggestion contrary to reasonable expectation.

HAWAIIAN VOLCANO OBSERVATORY.

A SKETCH OF THE LIFE OF RICARDO MANUEL ARANGO

By A. P. Crary

Ricardo M. Arango, Consulting Engineer for the Republic of Panama, died at his home in the City of Panama, January 24th, after a long illness. He was born December 25, 1864, and was graduated with the degree of C. E. from the Rensselaer Polytechnic Institute, Troy, N. Y., in 1887. His first work after graduation was to make a survey under the direction of Pedro J. Sosa, a prominent Panamanian engineer, of 500,000 hectares of land in the Province of Bocas del Toro, conceded by the Columbian Government to the French Canal Company. This party did the first surveying work in that region. In 1889 he was appointed by the Columbian Government to take charge of surveys made necessary by a controversy between it and the Panama Railroad, over the filling of the present site of Colon.

Mr. Arango took an active part in the revolution of 1903 by which Panama secured its independence from Columbia, being of great assistance to his father, José A. Arango, who was a member of the original junta of separation. As member of the municipal council of the city of Panama, he signed the act of independence. He was the first chief engineer of the new republic.

Under Chief Engineer John F. Wallace of the Isthmian Canal Commission, Mr. Arango was consulting engineer for sanitary work in the City of Panama. Later he was made division engineer of the Burêau of Meteorology and River Hydraulics. As head of this bureau, he installed the first seismograph on the Isthmus and established the gauging station at Alhajuela on the Chagres River, from which advices of any floods could be telephoned, in advance, to those in charge of work on the lower reaches of the river. His services with the Isthmian Canal Commission were terminated in the fall of 1908. Soon after this he was appointed minister plenipotentiary and envoy extraordinary for the Republic of Panama to the Court of St. James, a post that he had to relinquish in 1909 on account of ill health. In 1910 he was again made chief engineer of the republic, and later consulting engineer, which position he held at the time of his death.

Mr. Arango was a man who loved his profession. Even during his long illness, when he had lost almost completely the use of his hands, he would take great delight in reading and studying engineering. It was wonderful how he had trained his mind so that he could transform equations, construct graphical diagrams, and do other things mentally, that are generally accomplished by paper and pencil. He was always genial and willing to help and give advice. He stood up couragously under his sickness, which deprived him of many pleasures and much work that go to make life worth living. He was always interested in public affairs, and so long as he could he took an active part in them. In his death Panama loses one of its best and most progressive citizens.

SEISMOLOGICAL NOTES

Slight earthquake causes disaster.—A slight earthquake at Chemnitz in Germany on December 15, 1913, caused the collapse of a tunnel while a passenger train was passing through. The locomotive and six cars were buried beneath the debris, which caused the loss of eight lives, and thirty-four persons received serious injuries.

Earthquake in Japan.—A strong earthquake was felt on the 15th of December 1913, over an extensive area in Japan, including the cities of Tokio and Yokohama, where the houses were rocked violently and the people greatly alarmed. No casualties were reported, and the damage was slight.

Disturbance felt in Pacific Ocean.—Second officer H. Claydon of the British steamer *Aorangi* reports that on the 19th of December at 12:15 p.m. in latitude 6° 20′ south, longitude 144° 15½′ west, a distinct submarine disturbance was felt. Again at 2:26 p.m. on the same day in latitude 5° 57′ south, longitude 144° 5′ west, another shock was felt more severe and longer than the first.

Slight earthquake at Seattle.—A shock of five seconds duration was felt in Seattle and some of the neighboring towns on December 25, 1913, at 6:40 a.m. Windows were rattled and lights were extinguished in some places, but no serious damage was done. At Edmonds, fifteen miles north of Seattle, two shocks were felt on the same date, one occurring at 2:45 a.m. and the other at 6:42 a.m.

A strong earthquake shock was recorded on January 30th by the seismograph of the University of Washington, lasting from 7:59 tiil 8:35 a.m. The needle moved two inches on the record.

Severe shocks in Greece.—Violent earthquakes caused great damage on January 6, 1914, to property in the provinces of Elis and Peloponnesus. On the 23rd of January, 1914, a severe earthquake shook the town of Lepanto, a seaport on the gulf of Corinth. Nearly every house in town was damaged and the fortress partly wrecked, but no one was injured.

Slight shock in Peru.—The seaport of Callao was shaken by an earthquake lasting fifty-five seconds at 1:45 a. m. on January 12, 1914. No lives were lost. A tidal wave was reported to have flooded the basements of the naval school and several hotels at Laputa immediately after the earthquake.

Earthquakes and volcanic eruptions in Japan.—On the evening of January 12, 1914, a rapid series of earthquakes, reported to be over 350 in number, was felt in Kagoshima, Japan. On the following day, after more violent shakes, the volcano of Sakura-Jima on the island of Sakura broke out in violent eruption, causing considerable damage and loss of life both on that island and in the town of Kagoshima. The first reports were wildly exaggerated, but the damage was extensive. On the island of Sakura 840 houses, comprising nine villages, were destroyed out of a total of eighteen villages. The number of deaths was probably small.

In the town of Kagoshima eighteen deaths were reported, eighty-seven persons severely injured, and seventy-one slightly hurt. Thirty-five houses collapsed and one hundred and eighteen were damaged. The principal public buildings were not injured.

Two further violent eruptions of the volcano Sakura-Jima occured on January 17th, causing the collapse of many more buildings; and many of the inhabitants who had returned to Kagoshima after the first eruption, again fled in terror. Further particulars are given in *Nature*, Jan. 22, p. 589.

Knoxville, Tennessee.—Two earthquake shocks were reported from Sweetwater and Niota, Tennessee, on January 23d, by Mr. C. H. Gordon, Assistant State Geologist. The first shock stopped the clock in the railroad block-house at 10:24 p.m., and the second and much lighter one was recorded at 10:41 p.m. The signals and switches rattled violently, and a lamp chimney was nearly shaken off a lamp and a rumbling noise accompanied the movements.

Stanford University, California.—On January 23, 1914, at 7:34 p. m., a slight earthquake shock was reported by several members of the faculty and students both on the campus and in Palo Alto. Two distinct shocks were felt, the first one being very short followed by an interval of a few seconds, and then a second shock of several seconds duration, which caused a slight creaking of doors and rattling of windows.

This shock was also reported by Mr. Horace Davis and Mr. L. L. Hohl from San Francisco as lasting from ten to fifteen seconds and of an intensity such that two small statues on a shelf on the third floor of a building were thrown over. Reports sent in by the Spring Valley Water Company from their various stations in and around San Francisco agree very closely with the above as to the time and intensity of the shock.

Several shocks in Argentina.—Several violent earthquake shocks were felt on January 26, 1914, at Mendoza, which is the capital of the province of Mendoza, Argentina. The shocks were preceded by several pronounced subterranean rumblings. Mendoza is situated about sixty miles from the volcano of Aconcagua.

In New York and Canada.—On February 10, 1914, about 1:31 p. m., a fairly strong earthquake shock was felt throughout the northeastern part of the country. Its origin seems to have been in the northern part of New York State, and it was felt as far south as Philadelphia and Harrisburg, as far north as Quebec, as far east as Boston, and as far west as Preston, Ontario,—that is, probably over an area of 200,000 square miles. It is possible that its origin was the same as the earthquake of April 28, 1913, namely in the St. Lawrence valley, along the New York border; but the information is not yet sufficient to confirm this. The shock was distinctly stronger than the earlier one mentioned, but was not strong enough to do any real damage. A more detailed account will appear in the next number of the BULLETIN.

Earthquake in Cuba.— A strong earthquake felt at 2 a.m. on February 11, 1914, at Santiago de Cuba, created great excitement among the population. No reports of damage were received.

Series of shocks at Reno, Nevada.—Between 2 a.m. and 4:06 a.m.

on the 20th of February, 1914, a series of earthquake shocks were felt at Reno, which caused a rattling of windows and shaking of foundations, and awakening of many of the residents. Very little damage was done. Four distinct shocks were felt in Reno on March 1, 1914. The first occurred at 4:15 a.m. and was of several seconds duration. Two others were felt during the morning, and the fourth shortly after 5 p.m.

Three shocks in Maine.—Three distinct earthquakes were felt at Eustis, Maine, on the 21st of February, 1914. The first, which was light, occurred at 7:15 p.m. The second shock was felt five minutes later, and shook the houses. The third shock was light, and was recorded at 7:35 p.m. No damage was reported.

Record of distant volcanic earthquake.—In *Nature* for February 26, 1914, Dr. C. Davison calls attention to the evidence of the volcanic earthquake at the time of the Sakurajami eruption having been recorded at Laibach, Austria. He concludes that "it seems probable that Professor Belar is correct in assigning to the earthquake a place among the volcanic phenomena, and to its focus a depth considerably greater than is usual in volcanic earthquakes."

Southern states shaken by earthquakes.—In many towns in Georgia, Tennessee, Oklahoma, and the Carolinas numerous shocks were felt on the evening of March 5, 1914, which rattled windows, shook buildings, and caused mild excitement for a while. The seismographic records at Mobile showed that the tremors were light but rapid, indicating that the center of the disturbance was not far distant. No damage was reported.

Appalachian shock of March 5, 1914.—Our colleague, Professor C. H. Gordon of the University of Tennessee, sends us notes of an earthquake that appears to have been felt over a wide area through the southern Appalachian region: Tennessee, Georgia, Alabama, and South Carolina. It occurred shortly after three o'clock on March 5th. At many places buildings swayed, windows rattled, and there was considerable excitement, but no damage. The places from which reports of the shock were received were Knoxville and Chattanooga, Tennessee; Anderson and Greenville, South Carolina; Macon and Columbus, Georgia; Mobile, Alabama.

Distant disturbance recorded at Cleveland.—The seismograph at the observatory of St. Ignatius College recorded an earthquake on the 9th of March, 1914, which the Rev. Father Odenbach says was apparently in Japan, India, or China. The disturbance began at 12:45 a.m. and lasted until 2:00 a.m. There was a recurrence at 5:00 a.m. which continued until 6:00 a.m.

Hondo, Japan.—Reports received by cable on March 15th state that there was a serious earthquake that day in the prefecture of Akita on the island of Hondo, Japan. Many houses were destroyed and many lives were lost. It is also reported that the volcano Asama-Yama is in eruption. A copper mine at Tsundato is said to have caved in, and the fate of three hundred miners is as yet unknown.

Cleveland, Ohio, March 16, 1914.—The seismograph at the St. Ignatius Observatory recorded a distant earthquake at 2:36 a.m.

Mobile, Alabama.—The seismograph at Spring Hill College, Mobile, Alabama, recorded a distant earthquake on March 21st at 1:31 a.m.

Oregon, March 22, 1914.—A slight earthquake was felt throughout the city of Portland, Oregon, the morning of March 22d. Windows and dishes rattled and houses swayed, but no damage was done.

Death of Professor Mercalli.—The death of Professor Guiseppe Mercalli at Naples on March 19th is announced. He was the director of the Vesuvius Observatory, professor of seismology at the University of Naples, and the author of the Mercalli scale of earthquake intensities. He was born at Milan in 1850.

REVIEWS

MODERN SEISMOLOGY. By G. W. Walker. With plates and diagrams. 8°, xii+88 pages. London, etc., Longmans, Green & Co., 1913.

In the last quarter of a century the science of seismology, though advancing along its whole front, has progressed mainly in two lines. One of these relates to the displacements of the crust observed during great shocks and the distribution of earthquakes in space, and points the way to new views on the origin of earthquakes and to wider knowledge of those portions of the globe in which mountains are coming to birth or partially-formed ranges are continuing their growth. The other deals with the registration of "world-shaking earthquakes" and the evidence which their records afford as to that intricate and difficult problem, the nature of the earth's interior. Naturally, the one branch of the science is of the greater interest to geologists; the other appeals mainly to physicists. There is thus no little danger of the subject receiving partial treatment at the hands of either men of science. Mr. Walker is not unaware of the danger, for he refers to his ignorance of the geological developments. He looks at his subject from the physical point of view alone. But the title of his book is misleading. It should have expressed more clearly the fact that he is dealing simply with the "physics of earthquake-phenomena."

In this limited sense, however, his book is a useful contribution to the literature of seismology. Mr. Walker has a practical acquaintance with the working of four of the principal instruments that have added so much to our knowledge of earthquake movements. The observatory under his charge in the lonely district of Eskdalemuir in Dumfriesshire contains seismographs designed by Milne, Wiechert, Galitzin, and Omori. It is one of the best equipped geodynamic observatories in the world. The author's mathematical training enables him to appreciate the merits and defects of the different instruments. But the isolation of Eskdalemuir and its distance from scientific libraries are apparent in his somewhat incomplete acquaintance with the work of other seismologists.

The form of seismograph most widely adopted is that known as the horizontal pendulum, so called because, in oscillating, each point moves in a plane which is nearly horizontal, the line about which it rotates being as nearly vertical as it is in practice convenient or possible to make it. Mr. Walker remarks that "the horizontal pendulum adopted by Milne appears to have been independently invented in slightly different forms by different investigators, and it is difficult to assign priority." In reality, its history is simple and not without interest. One form was discovered in 1832 by L. Hengeller, a student in Munich. In 1851 a second form was devised by A. Gerard, an Aberdeen student. Nine years later, Perrot described an instrument resembling Hengeller's for measuring the lunar disturbance of gravity. In 1869 the Rev. Maxwell Close, of Dublin, and Professor Zollner independently rediscovered Hengeller's pendulum. The band of British workers in Japan made the next advances. Professor (now Sir) J. A. Ewing in 1880 invented a third form of pendulum, which he adopted in his well-known seismograph. In 1888-89 Dr. E. Von Rebeur-Paschwitz, of Merseburg, in Saxony, working on Zollner's model, arrived at a form similar to Ewing's. Two years later, in 1891, the late Professor Milne reinvented Gerard's pendulum, and gradually improved it until it reached the form now in use in so many British and foreign observatories. Lastly, in 1893, Mr. Horace Darwin reproduced in his bifilar pendulum the first or Hengeller's form, this being the eighth time in which the principle of the horizontal pendulum was discovered in about sixty years. Priority in recognizing the principle of the horizontal pendulum thus rests with Hengeller and Gerard; but, so far as regards its application to the construction of seismographs, we are indebted to Ewing, Milne, Paschwitz, and Darwin.

The merit of Mr. Walker's essay is due to its limitation (with one exception) to a definite field so small that it can be worked out in comparative detail within the compass of less than a hundred pages. He gives, in the first place, the general dynamical theory of seismographs. And here it may be remarked that, though Mr. Walker's treatment of the subject is mainly mathematical, it is yet possible for non-mathematicians to appreciate much of his reasoning. The three principal forms of seismograph—those of Milne, Wiechert, and Galitzin—and the method of installing them are described in some detail. Two of the later chapters, on the interpretation of seismograms and the determination of the epicentre, are specially valuable. The volume is well illustrated. The plates of the three principal seismographs might with advantage have been supplemented by diagrams showing the details of construction more clearly, these being obscured by the framework and cover represented in the plates. There are some interesting copies of actual records, especially those showing microseismic movements and the tilt produced by tidal loading, and those of the Zante and Dardanelles earthquakes of 1912.—*London Times,* January 23, 1914.

THE RELATIONSHIP OF ISOSTACY, EARTHQUAKES, AND VULCANICITY TO THE EARTH'S INFRA-PLUTONIC SHELL. By L. Leigh Fermor. *The Geological Magazine,* February 1914, pp. 65-67.

The article here cited is a very short but a very suggestive one. The author suggested in an earlier paper the existence within the earth's crust at an unknown depth "of a highly garnetiferous shell of rock, for which the name *infra-plutonic zone* or *shell* is suggested. This zone is situated at such a depth that pressure becomes a dominant factor in mineral transformations." He infers that if one can accept the necessity for the existence of this shell, then some theory of isostacy seems to follow, with the garnetiferous shell as the cushion on which the adjustments of the earth's crust take place. He points out that earthquakes are generally regarded as the results of attempts to relieve strains by fracturing, and it was suggested by Oldham that large earthquakes are accompanied by the passage of garnetiferous into non-garnetiferous rock or vice versa.

The author admits the possibility of the infra-plutonic shell being characterized, not by garnet alone, formed under high pressure, but "on the general principle of the existence of an infra-plutonic shell composed of dense minerals tending to pass exothermically into less dense minerals on release of pressure."

He recognizes the fact that temperature and water may be factors modifying these reactions to a certain extent, but he believes that at the depths considered, "pressure is the compelling factor in chemical changes, the chief function of high temperatures and water (when present) being the ensurance of the molecular mobility."

J. C. B.

ZUR FRAGE NACH DER URSACHE DER OSTBALTISCHEN ERDBEBEN. By B. Doss. *Centralblatt für Mineralogie, Geologie und Paläontologie*, 1914, no. 2, pp. 37-47.

In this paper Mr. Doss controverts the statements of F. de Montessus de Ballore that the earthquakes of the East Baltic region occur along structural lines. According to Mr. Doss, the earthquakes of that region are grouped around caves or sink holes, "doline," which sometimes are of great dimensions, as much as diameter of seventy-five meters and depth of forty-five meters. These caves are not arranged in a linear direction, except in so far as the limestones in which they occur themselves have a linear arrangement. The rocks are little disturbed, and the only deformation consists in very gentle folds. But the formations are filled with gypsum and limestone beds, and thus provide all the necessaries for underground solution and earth caves. Also the areal extent of the earthquakes there has never been great. They are local phenomena, in spite of their occasional violence, which speaks for the shallowness of the point of origin.

J. P. SMITH.

REPORT OF THE SEISMOLOGIC STATION OF THE NEW YORK STATE MUSEUM. *Museum Bulletin* 164, pages 28-30, Albany, N. Y., March 1, 1913. John M. Clarke, Director.

This station was established in March 1906, and is now under the immediate charge of Mr. R. W. Jones. Twelve tracings of earthquakes were obtained during the year ending September 30, 1912, as compared with nine during the preceding year, and nineteen during 1909-10. The instruments recorded heavy shocks in all parts of the world, and the files contain tracings of disturbances in California, Valparaiso, Kingston, Himalayan region, Turkestan, Messina, Mexico, Costa Rica, Iceland, Northern Alaska, and Turkey in Europe.

J. C. B.

COMPTES-RENDUS DES SÉANCES DE LA QUATRIÈME CONFÉRENCE DE LA COMMISSION PERMANENTE ET DE LA DEUXIÈME ASSEMBLÉE GÉNÉRALE DE L'ASSOCIATION INTERNATIONALE DE SISMOLOGIE. Réunies a Manchester du 18 au 21 Juillet, 1911. Rédigés par le Secrétaire Général R. de Kövesligethy.

This quarto volume of over three hundred pages contains much interesting and valuable material. Delegates from most of the important countries of the world attended this, the second meeting of the International Seismological Association.

Procès-verbaux des Séances.—The first thirty-two pages contain the minutes of the various meetings held, including the names of the delegates, address of welcome by the vice-chancellor of the University of Manchester, opening address of the president of the association, Professor Schuster, mention of all the reports and papers presented by the delegates, and numerous other matters.

Annexes-Beilagen.—Pages 33 to 138 give in full, under twenty-seven heads, various matters brought up during the meetings, including the report of the general secretary, financial reports, report of the work of the central bureau, report of the committee on catalog, reports of the various delegates concerning seismological work carried on in the countries represented by them, etc.

Conférences-Vorträge.—Pages 139 to 280 are given up to the nineteen formal papers presented at the meeting. These papers are all valuable contributions to the science of seismology, and should be consulted by every student of the subject. The titles and authors of the papers are as follows:

"Horizontal pendulum movements in relation to certain phenomena," by F. Napier Denison.

"Bestimmung der Lage des Epizentrums eines Bebens aus den Angaben einer einzelnen seismichen Station," by Fürst B. Galitzin.

"Beobachtungen über die Vertikalkomponente der Bodenbewegung," by Fürst B. Galitzin.

"Über eine dynamische Skala zur Schätzung von makroseismichen Bewegüngen," by Fürst B. Galitzin. (This paper was reviewed by H. O. Wood, *Bulletin of the Seismological Society of America*, 3, 90.)

"Beitrag zur Bestimmung der Fortpflanzungsgeschwindigkeit der Erdbebenwellen in den obersten Erdschichten," by K. Haussmann. (This paper was reviewed by E. F. Davis, *Bulletin of the Seismological Society of America*, 3, 43.)

"Auxiliary instruments for the interpretation of seismograms," by O. Klotz.

"Sur la possibilité de la prévision des tremblements de terre," by R. de Kövesligethy.

"On the transmission of the earth's vertical motion to floating bodies," by A. Lo Surdo.

"Bestimmung der Activität der seismischen Perioden," by J. Mihailovitch.

"Quelques causes d'erreur dans la détermination de l'heure dans les sismogrammes," by S. Navarro-Neumann, S. J.

"Déterminations dynamiques des modules d'élasticité de Young des roches," by E. Oddone.

"On the earthquake and elevation phenomena which accompanied the Usu-san eruption of 1910," by F. Omori.

"Tremor observations on the Usu-san and the Asama-yama volcanoes," by F. Omori.

"Sur les observations de la déformation du globe terrestre," by A. Orloff.

"The transmission curve," by H. F. Reid.

"The energy of earthquakes," by H. F. Reid.

"Earth movements and earthquakes during the elevation of mountain ranges," by H. F. Reid.

"Eine graphische Methode zur Bestimmung der Lage des Epizentrums eines Erdbebens," by C. Zeissig.

We hope to be able to publish reviews of more of these interesting papers.

Appendice-Anhang.—Pages 281 to 301 contain ten appendices relating to various matters of a miscellaneous nature.

S. D. T.

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

I. **Microseismic shock**: recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
II. **Extremely feeble shock**: recorded by several seismographs of different kinds; felt by a small number of persons at rest. some startled persons leave their dwellings.
III. **Very feeble shock**: felt by several persons at rest; strong enough for the direction or duration to be appreciable.
IV. **Feeble shock**: felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.
V. **Shock of moderate intensity**: felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.
VI. **Fairly strong shock**: general awakening of those asleep, general ringing of house bells; oscillation of chandeliers; stop-
VII. **Strong shock**: overthrow of movable objects; fall of plaster; ringing of church bells; general panic. without damage to buildings.
VIII. **Very strong shock**: fall of chimneys. cracks in walls of buildings.
IX. **Extremely strong shock**: partial or total destruction of some buildings.
X. **Shock of extreme intensity**: great disaster, buildings ruined. disturbance of the strata, fissures in the ground. rock-falls from mountains.

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THE LISBON EARTHQUAKE OF NOVEMBER 1, 1755.

By Harry Fielding Reid

The region in which this earthquake occurred, its severity, the damage and loss of life due to it, the distance to which it was felt, the great sea-waves to which it gave rise, the agitation of the waters of distant lakes and ponds which it caused, have all united to make it probably the most notable earthquake of history. It is also to be remembered that the power of an earthquake to agitate lakes and ponds at very great distances was first noticed at the time of the Lisbon shock, and that it incited the first serious scientific attempt to explain the cause of the great sea-waves that follow some submarine earthquakes.[1] Lyell, in his delightfully written "Principles of Geology," has made English-speaking people familiar with the main facts of the earthquake; and in our day Woerle has given a more complete account based on a study of the contemporary records.[2]

The imagination was drawn upon much more freely in 1755 than at the present time, to give vividness to narratives, and many remarkable phenomena were described which could not have occurred; moreover, reports were not examined very critically, and sufficient care was not taken to avoid referring to the Lisbon earthquake events which took place at other times and which had no connection with it. As a consequence, many false conceptions of the effects of this earthquake have become general; and it is the object of this communication to point out some of them, and to apply our present knowledge to the elucidation of some phenomena not heretofore explained.

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[1] Geschichte und Naturbeschreibung der merkwürdigsten Vorfalle des Erdbebens, welches an dem Ende des MDCCLV Jahres einen grossen Theil der Erde erschüttert hat. By Immanuel Kant, 1756, "Sämmtliche Werke," 1839, 6, 227-280.

Conjecture concerning the Cause and Observations on the Phenomena of Earthquakes; particularly of that Great Earthquake of November 1, 1755, which proved so fatal to the City of Lisbon, and whose Effects were felt as far as Africa and more or less throughout almost all of Europe. By Rev. John Michell, M.A. *Phil. Trans. R. S.*, 1760, **51**, 556.

[2] Der Erschutterungsbezirk des grossen Erdbebens zu Lissabon. „Inaugural Dissertation von Hans Woerle," Munich, 1900, 150 pp. and two maps; also published in "Gunther's Münchner Geog. Studien."

Notices of the earthquake were collected by a number of persons and published in 1756 or shortly after; several treatises on earthquakes also made their appearance. Woerle gives a list of the collections and treatises from which he has drawn his information; a severer criticism than he exercised is necessary to avoid serious errors. As pointed out by Choffat,[3] he has neglected the Portuguese and Spanish writers, whose accounts would furnish a much better idea of the distribution of intensity in the Spanish peninsula than we now have. In addition to the *Transactions of the Royal Society,* (which indeed contains some of the most important and reliable of the early accounts), I have been able to consult but few of the original European contemporary records, and must rely on von Hoff's[4] and on Woerle's report of them; but in spite of this, I think some general errors can be disposed of.

The Lisbon quay.—The story of the sinking of the quay at Lisbon to unfathomable depths has become generally current. It seems to depend on a letter of an English merchant named Braddock who was in Lisbon at the time; it was published in London in 1787 by Rev. Chas. Davy. A German translation of the letter is given by von Hoff.[5] It reads more like literature than science. Braddock was not an eye witness of the destruction of the quay; he merely repeats the account of a ship's captain, who asserted that a great sea wave, twenty feet high, rushed over the quay immediately after a severe shock, and that he then saw the quay disappear; and a few days later Braddock found no signs of the quay, but there was deep water where it had been; and in one place he says it was almost unfathomable. He gives no hint how he was led to this remarkable conclusion. Lyell states that Whitehurst ascertained the water to be 100 fathoms deep where the quay had been. He adds that he was informed in 1841, "that no part of the Tagus was then more than thirty feet deep at high tide, and an examination of the position of the new quay, and the memorials preserved at the time and manner in which it was built, render the statement of so great a subsidence in 1755 quite unintelligible." Mr. J. Latham was on the River Tagus at the time of the shock, and wrote six weeks later that the quay "was turned bottom upwards."[6] Mr. Wolfall, surgeon, and John Mendes Saccheti, M.D., F.R.S., each wrote two letters from Lisbon immediately after the earthquake,[7] but made no mention of the quay; nor is it mentioned in the rather intelligent account of Manoel Soares, published in Lisbon in 1756, and re-published in part in the *Transactions of the Seismological Society of Japan*, **12**, 5-19, 1888.

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[3] *Die Erdbebenwarte*, 1904-5, 4, 15, 16.

[4] Von Hoff, "Veränderungen der Erdoblerfläche," 1840, 4, 425-450.

[5] Loc. cit., pp. 428-431. See also Lyell, chapter xxx; Woerle, p. 36.

[6] *Phil. Trans.*, 1755, 49, 411.

It will be seen that the reported sinking and disappearance of the quay rests on very insufficient evidence; indeed the evidence is in some respects contradictory. Lisbon is not situated on the seacoast, but on a shallow expansion of the Tagus River, and the quay could not have sunk into deep water as a part of a landslide. Lyell suggests that a fissure may have opened and swallowed up the quay; but such fissures as did appear in the ground were apparently of secondary character, and too small for such a result; for the origin of the earthquake must have been some distance off shore, as indicated by the later arrival of the sea-wave. It is probable that the quay was shattered by the shocks, and that the stones of which it was built were scattered by the sea-waves; the distress and misery in the city must have confined the attention of all to the pressing needs of the moment, and no one had time or disposition to determine what really became of the material of the quay. And the bodies of those on the quay and the boats near it must have been carried far away by the great waves, which explains the report that they were never found again. Although the quay was undoubtedly destroyed, the story of its complete disappearance rests on wholly inadequate testimony. Like the report of Mr. Wolfall, that he saw "the walls of several houses that were standing, open from top to bottom, more than a quarter of a yard, yet close again so exactly as to leave no signs of injury," the story of the engulfing of the Lisbon quay must be ascribed to the love of the marvelous and the mysterious, which has not even yet entirely disappeared from the accounts of earthquakes.

The epicenter of the shock.—Choffat points out that the region of very high intensity embraces all the southwestern part of Portugal, being highest along the coast, but does not extend far north of Lisbon; the northwestern coast of Africa was also pretty strongly shaken. These considerations, the arrival of the sea-waves some time after the shock, and the fact that the earthquake was more severe in the Madeira Islands than in the northeastern part of Spain, suggest that the origin lay in a fracture beginning under the sea south of and not far from

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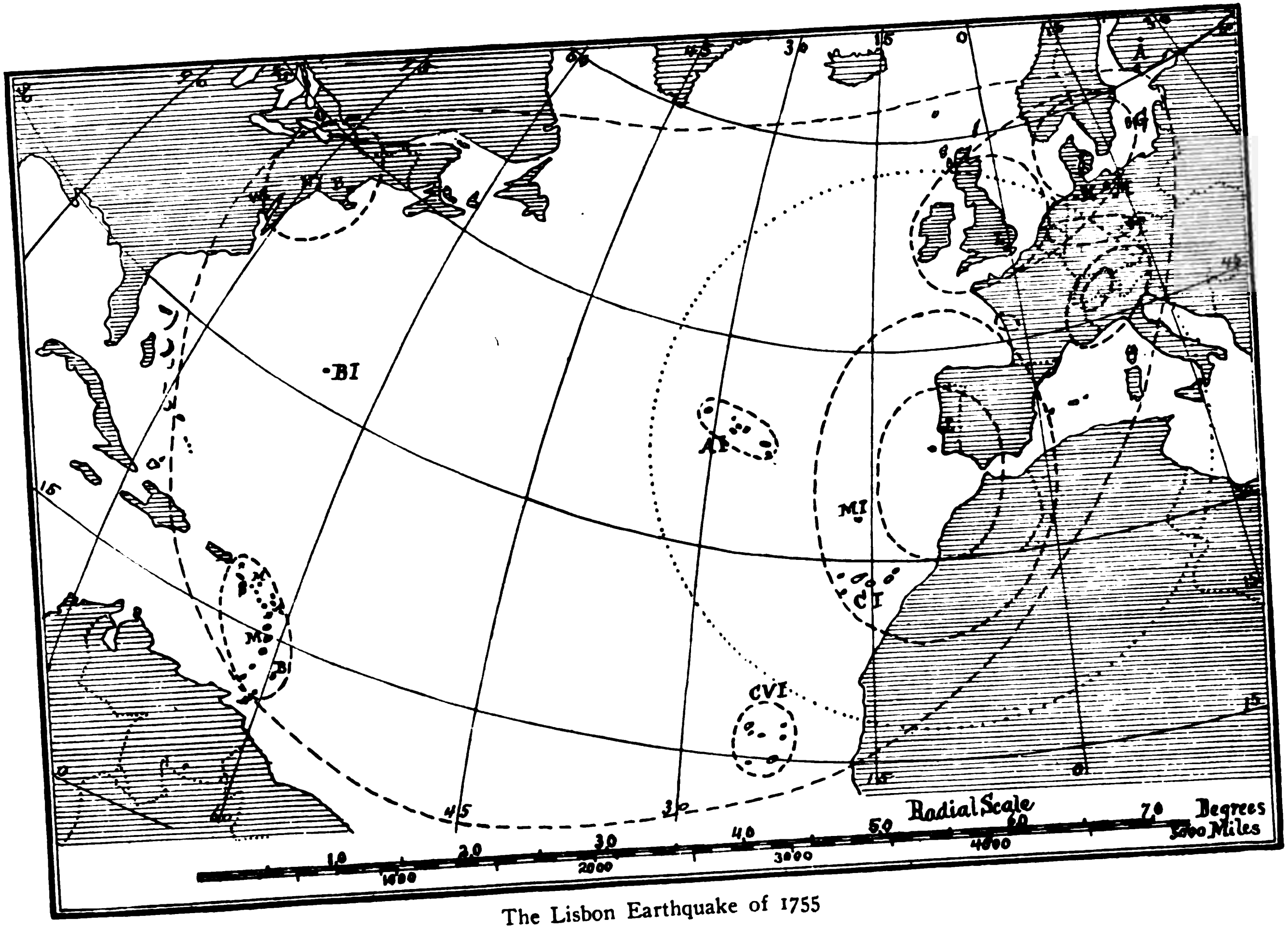
[7] Same, 402-411.



The Lisbon Earthquake of 1755

Lisbon, and extending for some distance in a somewhat southwesterly direction. It does not seem possible to locate the epicenter more definitely. I have selected a point lying in latitude 38° N and 10° W as the point from which to reckon distances (see map), but it must be remembered that this is only for convenience. Woerle has placed the center of the earthquake a little further north, opposite Lisbon; the difference is not material.

The time of the shock.—Naturally the reports as to the time of the shock differ. But Woerle concludes from a comparison of them all that the earthquake began at 9:40 with a fairly strong shock, followed very shortly by two others of great severity which were the cause of the great disaster. Another fairly strong shock occurred at 12 o'clock, and many lighter ones during the day and on succeeding days. We shall take 9:40 for the time of the shock in any calculations that require the time as a basis.

The disturbed regions.—Woerle has indicated on his map, drawn on Mercator's projection, the regions shaken according to his researches. The map is drawn on a radially equidistant projection, with the point 38° N, 10° W as the center; all distances and directions measured from this point are correct. The tangential scale increases with the distance from the center; for the eastern half of the map this is negligible, but it produces some distortion in the far western part. The broken-line ovals were copied from Woerle's map, and enclose regions which he concludes were shaken as a result of the earthquake. The outer curve encloses all of these regions, and represents the generalized disturbed area; in Woerle's map its form is much more symmetrical, on account of the distortion due to Mercator's projection; the present map gives a truer representation of the form of Woerle's curve.

The Atlantic islands and Europe.—The intensity of the shock in the Canary Islands and in the Azores was less than at Madeira. The decrease in the intensity in the interior of Africa and the limit of the shaken area in that continent, are of course quite unknown. According to Zimmerman[8] the shock was severe in the Cape Verde Islands and was slightly felt as far east as Cairo. The distance of the latter place (34°) makes the statement respecting it quite incredible; the Cape Verde Islands may possibly have felt the shock very slightly; they are only a little more distant than places in northern Germany, where we shall see that the shock was felt. But the title of Zimmerman's book leads us to expect marvelous rather than accurate accounts of natural phenomena, and his statement cannot be accepted without corroborative evidence, which does not seem to exist. The shock was felt throughout the Spanish peninsula, but diminished in intensity towards the northeast. France, with the exception of small regions near the mouth of the Garonne in the west, in the southeast, and along the shore of the English Channel, did not report the shock. Southern Italy was unaffected, but northern Italy and the region of the Alps were shaken. It is unnecessary to continue the description. A glance at the map will show the regions, enclosed by ovals, where the shock was reported; an inner oval indicates a higher intensity within it. The reports from central and northern Europe are often indefinite or contradictory. In places the shaking was felt, but the phenomena usually mentioned as proof that the earthquake was observed were the agitation of the water of lakes, ponds or bays, the swinging of chandeliers in the churches (where services attracted the people because it was All Saints Day), the variation in the flow of springs or the muddying of their waters. None of these phenomena can rightly be used to define the shaken area. All great earthquakes shake the whole earth, and can be registered by sufficiently sensitive seismographs anywhere, but the so-called "shaken area" is usually limited to the area within which the earthquake can be *felt,* say the area enclosed by the isoseismal III of the Rossi-Forel scale. Great earthquakes send out long surface waves with periods of from ten seconds to twenty-five seconds or more, and these are capable of producing the phenomena mentioned above far beyond the limits of sensible motion. Throughout central and northern Europe the earth movements, due to these long waves, must have had a range of several centimeters, and with their long periods were well adapted to swing chandeliers, and start seiches in ponds, even though the movement was too slow to affect the senses. In Sussex and Surrey, England, where the waters of several canals and ponds were strongly agitated, it was expressly stated that "not the least tremor or motion of the earth was felt in any of these places."[9] The large range of the vibrations would also be effective in clearing the passages of some springs, in obstructing the flow of others, and in disturbing mud or clay and thus rendering the waters turbid.

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[8] "Wunder der Urwelt," quoted by Woerle, date not given.

Ponds and suspended lamps may be looked upon as forms of seismographs; the simple pendulum is the form in general use in Italy; and Grablowitz has invented his *vasa sismica* for recording earthquakes, which consists merely of a tank 1.60 meters in diameter containing water about one meter deep; on one side of the tank is a float which registers the movement of the water caused by the earthquake disturbance. Even without magnification these instruments can register unfelt disturbances, particularly where there is synchronism of periods.

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[9] *Phil. Trans.*, 1755, **49**, 353.

Struck by the apparent discontinuity of the areas over which the shock was felt, the anomalous high intensities manifested by some of them, Woerle adopts an earlier suggestion, that these several areas were the centers of relay earthquakes, started by the Lisbon disturbance. We shall see that this idea is the result of an uncritical examination of the evidence. For instance, in describing the disturbance in Switzerland, Woerle refers (among other references) to a letter from the Rector of the College of Jesuits at Brigue.[10] This latter narrates that several earthquakes were felt at Brigue in 1755, and particularly on November 1st, and adds: "And from that time, especially in the night, the walls were perceived by several persons to tremble." He then goes on to describe a severe earthquake on December 9th. I think the only reliable inference to be drawn from this letter is that entirely independent earthquakes occurred at Brigue, and *possibly* the Lisbon shock was felt. There seems to have been very general agitation of the waters in the Alpine region, and I think it not at all improbable that the earthquake may have been slightly felt there; but the evidence does not seem very satisfactory.

In central Germany the evidence is contradictory; but positive evidence is always more reliable than negative; and we may, I think, believe that the shock was sensible in that region. In Hamburg and its neighborhood the shock seems to have been slightly felt, for an account of it was published in Glückstadt, nearby, on November 5th, whereas the report of the Lisbon earthquake was not received until November 29th. Woerle states distinctly that the shock was felt in the province of Dithmarschen, a little to the northwest; and the evidence seems to establish that it was felt at Malchow, 150 kilometers east of Hamburg.[11]

It may be well to mention the oft repeated story of changes in the spring at Teplitz, in Bohemia (*T* on map). One account is contained in a letter from Father Joseph Steplin,[12] who derived his information directly by inquiry from the President of the Supreme Royal Council (presumably at Teplitz). He writes: "On the first of November of the last year 1755, between eleven and twelve in the morning, the chief spring cast forth such a quantity of water that in the space of an hour all the baths ran over. About half an hour before this vast increase of the water the spring grew turbid, and flowed muddy; and having stopped entirely near a minute, broke forth again with prodigious violence, driving before it a considerable quantity of reddish oker, *Crocus Martialis*. After which it became clear, and flowed as pure as before; and continues still to do so; but it supplies more water than usual, and that hotter, and more impregnated with its medicinal quality." De Montessus de Ballore[13] quotes with approval Knett's view of this event as a simple coincidence, which could have no possible relation to the Lisbon earthquake. But let us examine the facts. When we consider the difference of time between Lisbon and Teplitz, we find that the large waves of the disturbance must have reached the latter place about 11:20 in the morning, which corresponds satisfactorily with the time of the first change in the spring. Although no sensible motion was reported from Teplitz, it was nearer the center of the shock than places in northern Germany where the shock was felt, and we shall see that the river was agitated at Åbo, Finland, which is half as far again from the centrum as Teplitz. Although it is quite impossible to say that the changes in the spring were related to the earthquake, it is to be noticed that the distance of Teplitz is not so great as entirely to preclude all influence of the shock, that the changes reported are such as might easily be brought about by an earthquake, and that such an effect would not at the present time be considered marvelous or mysterious. But we are not likely ever to know the truth.

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[10] Same, 616. See also p. 511 for an account of a strong earthquake felt in Brigue on November 14, 1755.

[11] Woerle, 62, 63, 64, 69. Woerle does not make it perfectly definite that the Glüchstadt account describes a sensible motion and not merely the agitation of the waters and the swinging of hanging lamps.

The reports of the effects of the earthquake in Scandinavia are too sensational to be credible, such as the statement that on the shores of the Fryken and the Stora Leed lakes the ground rose and fell like great waves,—it is more likely that water-waves rose and fell on the shores; on the island of Gottland three large trees were reported overthrown by the shock. If these events happened at all, they must have been due either to a relay earthquake or to an independent shock which occurred at the same or at some other time, and which has become confused with the more famous Lisbon earthquake; Woerle has rejected some reports on the latter ground, and some which he has accepted must be rejected for the same reason. Mallet reports that a ship near the southern end of Norway felt the shock; and that it was felt at Christiansand at 4 a.m. But the shock of the Lisbon earthquake could not have reached Christiansand before 11 a.m. local time. This suggests an independent shock in or near Norway.

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[12] *Phil. Trans.*, 1755, **49**, 395-396. The letter is dated at Prague, January 30, 1756.

[13] "La Science Séismologique," 425.

Mallet notes that the shock was felt in Denmark and also in Iceland and Greenland;[14] he only gives general references for his information about the earthquake; Woerle does not mention Denmark at all, and gravely doubts that the shock was felt in Iceland and Greenland. The distances from the origin of the shock to these countries are so great that we cannot accept Mallet's statement without more definite evidence; it is to be noted that Mallet records von Hoff's opinion that the reports from Iceland and Greenland are doubtful.

Nearly all the reports from Holland refer to swinging lamps or disturbed waters, but in a few places the shock seems to have been felt.[15]

Turning now to Great Britain, we learn that some people thought they felt the earthquake in Kent, southeastern England,[16] and that a gardener near Reading, where a pond was strongly agitated, claimed that he felt a violent trembling of the earth; a second account of the same pond does not mention any motion of the earth.[17] In the same neighborhood, a house was reported to have been strongly shaken, and two dwarf trees to have been split.[18] At Petworth, about twenty-five miles northeast of Portsmouth, a large rock was supposed to have been split open, but the account in the *Philosophical Transactions* clearly states that the rock was in this condition three months before the account was written (November 26, 1755).[19] In the lead mines of Derbyshire, about the latitude of Liverpool, five shocks were felt in the course of twenty minutes; the second shock was the strongest, and alarmed the miners. At the surface of the ground the overseer "felt one shock, which very sensible raised him up in his chair, and caused several pieces of lime or plaster to drop from the sides of the room." The time was about 11 a.m. A fissure was also formed in the ground about a foot deep and six inches wide.[20] This was undoubtedly a local shock, and it does not seem possible to know if it had any relation to the Lisbon shock. The latter was reported to have been noticed at Cork, Ireland.[21]

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[14] *B. A. A. S.*, 1852, p. 167.

[15] Woerle, 61.

[16] *Phil. Trans.*, 1755, 49, 360.

[17] Same, 360.

[18] Same, 366.

[19] Same, 359; Woerle, 66.

North America.—"According to a notice from Boston, several strong shocks were felt there at 12:30 p.m.; all Pensylvania was disturbed by a light shaking. In the neighborhood of Lake Ontario movements of the ground were already noticed in the last days of October; but on November 1st the lake rose with great violence five and a half feet, three times within a half hour." This, translated freely, is Woerle's account of the effect of the earthquake in North America.[22] He gives no reference for the statement regarding Boston and Pennsylvania. His reference for the disturbance near Lake Ontario in October is to a letter[23] "from Governor Belcher's Lady: dated Elizabethtown, New Jersey, October 22, 1755," in which she writes: "A person lately come from the camp [at Fort Oswego, on lake Ontario] reports, that about a fortnight since, that lake rose and fell five feet and a half, three several times, in the space of half an hour." This contains no suggestion of any movement of the ground. Seyfart, who published "Allgemeine Geschichte der Erdbeben" in 1756, is Woerle's authority for the disturbance of Lake Ontario on November 1st; but it is quite evident that Seyfart's account is merely a repetition of Lady Belcher's information, with the date confused; the German account is a literal translation of Lady Belcher's letter.

The vibrations of the Lisbon earthquake would have reached Boston about 6 a.m. and not at 12:30 p.m.; and the sea-waves would not have arrived before the night. If this earthquake was felt in America there must be some local account of it; particularly as a very severe shock felt all over the eastern colonies on November 18, 1755, and the dreadful news of the destruction of Lisbon, which arrived about a month later, directed the attention of everyone to such phenomena.[24] The contemporary files of the *Boston Gazette*, the

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[20] *Phil. Trans.*, 1755, **49**, 399-402.

[21] Same, 419.

[22] Woerle, 80.

[23] *Phil. Trans.*, 1755, **49**, 544.

[24] After describing the earthquake of November 18, 1755, Minot, in his "History of Massachusetts Bay," Boston, 1798, 1, 262, goes on to say: "Such an extraordinary convulsion of the earth, from the circumstances of the people, and their cast of character, operated strongly upon their minds in a moral view; and re-

Pennsylvania Gazette, the *New York Gazette*, the *New York Mercury* and the *Connecticut Gazette* have been examined; and although accounts of the earthquake of November 18th, and of the arrival of ships bringing news of the Lisbon shock, are given, there is no hint that the latter was noticed in the colonies. Many early histories, diaries, memoirs, and transactions of historical societies have been scanned, with the same result.[25]

In the *Philosophical Transactions*[26] there are three letters regarding the earthquake of November 18th from Boston, New York and Philadelphia respectively. The last one, dated December 1, 1755, narrates: "About four of the clock the 18th of November last, this province was pretty generally alarmed with the shock of an earthquake . . ." This is probably the source whence information reached Woerle in a roundabout way, and which led to his statement that "all Pensylvania was disturbed by a light shaking" on November 1st.[27]

Samuel Williams, Professor of Mathematics at Harvard College, described the various earthquakes felt in New England to his date,[28] but did not include the Lisbon shock; after describing the earthquake of 1844, he says: "The next earthquake that shook the whole country was in the year 1755, November 18," etc. William T. Brigham in his list of New England earthquakes[29] refers to the Lisbon shock and says (erroneously) that it was felt from Iceland to Morocco and from Bohemia to the West Indies, but does not mention North

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ligion offering a consolation more stable than any temporal support, was resorted to with fervour, which distant danger or the regular approach of misfortune never inspires. The places of public worship were frequently and universally attended by all ranks of people; and when they became informed of the more dreadful catastrophe which followed the same natural causes in Europe, a renewed sensation resulted from their escape when apparently on the verge of a like general destruction. The government of Massachusetts Bay noticed this solemn alarm by appointing a day of humiliation and prayer, in acknowledgment of the distinguishing mercy of God, and in submission to his righteous judgments."

[25] I am indebted to Professor J. B. Woodworth, of Cambridge, Professor Franklin B. Dexter, of New Haven, and Mr. George Francis Dow, of Salem, for examining early records not easily accessible to me.

[26] *Phil. Trans.*, 1755, **49**, 439-444.

[27] It is suggestive that the name of the state is spelt *Pensylvania* in the *Philosophical Transactions* and by Woerle, though the usual spelling has always been *Pennsylvania*.

[28] "Observations and conjectures on the Earthquakes of New England." *Mem. Amer. Acad. of Arts and Sciences*, 1785, **1**, 260-311.

[29] "Historical Notes on the Earthquakes of New England," 1838-1869. *Mem. Boston Soc. Nat. Hist.*, **2**.

America. The last two references are not original sources, but evidently the writers found no grounds in their researches for believing that the Lisbon earthquake was felt in New England.

John Winthrop, a man of very considerable attainments and standing, who was Professor of Natural Philosophy at Harvard College at the time, sent a careful account of the earthquake of November 18th to the Royal Society, which was read January 13, 1757;[30] and it is a most significant fact that the idea that the Lisbon shock produced noticeable effects of any kind in North America does not seem to have entered his mind. Winthrop gave public lectures on earthquakes, in which he argued that, on account of the distance, the reported disturbances, or "eruption," at Barbadoes could not be due to the Lisbon earthquake. Barbadoes is about three hundred kilometers further than Boston from Lisbon. It is incredible that the Lisbon shock should have been felt in New England and that Winthrop should not have known it and have mentioned it.

At the end of his dissertation, Woerle quotes Seyfart, that "in the province of Connecticut the ground in consequence of the motion resembled the waves of the sea." This expression occurs in the *Connecticut Gazette* of November 22, 1755, referring to the earthquake of the 18th. The two preceding issues, of November 8th and November 15th, make no mention of an earlier shock.

It is impossible to prove a general negative, but the entire absence of local contemporary reference to any effect of the Lisbon earthquake in New England, and the fairly evident application to the Lisbon earthquake of reports concerning the earthquake of November 18th, force upon us the conviction that the Lisbon earthquake produced no sensible effects in the American Colonies.[31]

The Lesser Antilles.—Woerle tells us that the first shock was perceived in the Lesser Antilles towards three o'clock in the afternoon, and that a series of very high waves were seen at several islands; and he adds that at Barbadoes the waves came an hour after the beginning of the earthquake.[32] The time of the arrival of the water-waves is undoubtedly correct, but as the large earth-waves of the earthquake shock must have reached the Antilles before seven o'clock in the morning, the above account does not indicate that the Lisbon shock was felt in the Antilles. Humboldt, writing more than fifty-five years after the Lisbon shock about the earthquake which destroyed Caraccas on March 26, 1812,[33] attempts to show that the Caribbean Sea, the Gulf of Mexico and the whole basin of the Mississippi River form one great dynamic unit, and adds: "When we reflect that the great earthquake of Lisbon, of the 1st of November 1755, was felt almost at the same moment on the coasts of Sweden, at Lake Ontario, and at the Island of Martinico, it will not appear too daring to suppose that all the basin of the West Indies, from Cumana and Caraccas as far as the plains of Louisiana, may be simultaneously agitated by commotions proceeding from the same center of action." We have seen that the earthquake was most probably not felt in Sweden, and certainly not at Lake Ontario. Humboldt gives no authorities for his statements, and we are forced to believe that he is repeating reports supposed at that time to be true; and we cannot regard his statement as authoritative.

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[30] *Phil. Trans.*, 1757, **40**, 1-18.

[31] Earthquakes were also felt in Europe on November 17th and 18th. This may have contributed to the error.

[32] This is based on a statement published in 1757 which I have been unable to consult.

South America.—Ships brought news that the Portuguese warehouses at Pernambuco on the eastern coast of Brazil were razed to the ground.[34] This is surely a sailor's yarn; for Brazil is quite aseismic; severe earthquakes are unknown there. Professor John C. Branner has published a list of Brazilian earthquakes.[35] He writes: "I have brought together in this paper all the information it has been possible to gather from a considerable acquaintance with the literature of Brazilian geology." The first earthquake he reports is in 1744; but none whatever are reported in 1755. It seems fairly certain that the report of Pernambuco is entirely false, and indeed Woerle himself does not include this city in his "shaken area," though he does not give any reason for not doing so.

Ships at sea.—A number of ships off the coast of Portugal, some of them as much as a hundred and fifty or two hundred miles distant, were strongly affected by the shock.[36] I may add an item from the *Pennsylvania Gazette* of December 18, 1755; "By Captain Johnson who arrived here [in Boston] Tuesday last five weeks from Lisbon." Captain Johnson reported a strong agitation of his ship when about sixty leagues out from Lisbon, four or five days after he had left that port. He added: "This happened about a fortnight before the terrible shock of an Earthquake felt in these Parts on the 18th day of November past." He evidently knew nothing about the Lisbon earthquake at that time. The first published account of it in America seems to have been in the *Boston Gazette* of December 22, 1755, based on the report of Captain Hilbert, who left Cadiz November 11th and arrived at Marblehead December 15th.

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[33] "Travels to the Equinoctial Regions," Book V, chapter i, Williams' translation, London, 1819, p. 10.

[34] Woerle gives this report on the authority of J. H. R., who collected notices of the earthquake and published them at Frankfurt and Leipsic in 1756.

[35] *Journal Geology*, 1910, **18**, 327-335.

[36] Woerle, 80-82.

The area shaken.—Many estimates have been made of the extent of the region sensibly shaken by the Lisbon earthquake; these vary from 4⅓ million square km. or 1/120 of the earth's surface to 38½ million square km. or 1/13 of the earth's surface. Woerle[37] estimates the land area within his ovals, known to have felt the earthquake (including a part of New England), at 2,430,000 square km., and the total area shaken at about 35 million square km. It is to be noted that Lisbon lies close to one side of Woerle's shaken area; by excluding the distant regions where, as we have shown, the shock was almost certainly not felt, this eccentricity practically disappears. (The limits in Africa are of course entirely imaginary).

We shall probably get a fair idea of the region sensibly shaken, say within the isoseismal III of the Rossi-Forel scale, by looking upon it as a circle of radius equal to the distance from Lisbon to Hamburg, 20½°; the area of this circle is about 16 million square km., or a little more than three per cent of the earth's surface.

Disturbance of the waters.—The Lisbon earthquake is famous for the agitation it caused in the waters of distant ponds, lakes and rivers, and the high sea-waves it sent out to remote shores. Before the shock it was not suspected that the effects of an earthquake could be observed at such very great distances. Many of the inland waters of southern, middle and northern Europe were set in oscillation; the most distant place reporting such a disturbance was Åbo in Finland, 31½° or 3500 km. from the assumed origin. The sea-waves were very marked in the Antilles, distant 51°, or 5700 km.

Many attempts have been made to explain how the earthquake caused the disturbance of the waters, and the discussion is not yet closed; some light, however, can be thrown on the question. It was quite natural to divide the phenomena into two classes: (*a*) the agitation of inland waters, and (*b*) the agitation on the shores of the open sea and its branches. This classification, which was made by Kant, has been adopted by von Hoff and by Woerle; the latter indicates on his maps that sea-waves washed the greater part of the shores of the north Atlantic, the western part of the Mediterranean, the North Sea and the Baltic; and that the agitation of the inland waters extended as far north as southern Scandinavia, and as far west as Lake Ontario. We have seen that the reports about Lake Ontario were erroneous.

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[37] Pp. 117-118.

A better classification is to divide the disturbances according to their genesis, into (*a*) agitation due to the actual vibrations of the earthquake; (*b*) agitation due to the arrival of sea-waves propagated across the ocean to distant shores. These two classes are easily distinguished; the disturbances due to the vibrations occurred within a few minutes of the time of the earthquake; it would only take about fifteen minutes for the large earth-waves to reach Åbo, the most distant place where the first class of agitation was reliably reported; whereas, even at Lisbon, Woerle reports an hour's interval between the earthquake and the arrival of the great sea-waves; and they only arrived in England and Ireland several hours later. We shall call the first class *oscillations* and the second class *sea-waves*. It might appear that the two classifications were practically identical, but this is far from being true; many cases of agitation at seaports which are really due directly to the vibrations of the earth have been looked upon as due to sea-waves, with a corresponding misapprehension of their character.

Oscillations.—The difficulty of supposing that ponds could be disturbed by an earthquake at places where the earth movement was imperceptible, and therefore supposed not to exist, led to the search for other means to explain the disturbance of distant waters.[38] The phenomena of seiches were naturally invoked; these periodic elevations and depressions of lakes were supposed to be due to continuing meteorologic conditions, before their true nature was known; it was only in the seventies that Forel showed that seiches were balanced oscillations, or stationary waves in lakes. The disturbance of the waters at the time of the earthquake was considered a coincidence, and was supposed to be independent of it;[39] but the great number of ponds, lakes, etc., which were agitated, the fact that the agitation occurred within a few minutes of the shock, and the further fact that ponds are frequently disturbed at the times of great earthquakes, render a causal relation between the two phenomena practically certain. Moreover, the reports show that on November 1, 1755, the air was perfectly still at many places where the ponds were disturbed.

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[38] Kant, however, in 1756, thought that movements too gentle to be felt might be able to cause agitation of small bodies of water, but that a much stronger movement would be necessary to agitate the ocean. Loc. cit.

[39] This view is taken by Hoernes even as late as 1893; "Erdbebenkunde," 125-200.

Forel, whose classic work on the seiches of the Lake of Geneva is so well known, sought in vain for a relation between seiches and earthquakes.[40] He found that the earthquakes felt on the shores of the Lake of Geneva, some of which reached an intensity of VI or VII (R-F scale), did not produce even the smallest seiche. De Rossi knew that some felt earthquakes caused no visible movement of the low-power pendulum seismographs then in use, whereas other earthquakes, though unfelt, set the pendulums in oscillation; he ascribed this difference to the absence or existence of synchronism of period; and suggested that the same explanation applied to the production of seiches. But Forel pointed out that the fundamental period of the Lake of Geneva is about seventy-two minutes, and that the periods of the multinodal oscillations are still to be expressed in minutes, whereas the longest period of earthquake vibrations was, according to the observations in Japan, four to seven seconds. These vibrations were considered extraordinarily slow; they were recorded during a disturbance on April 18, 1889, with a range doubtfully put at 17 mm. At the same time West "observed the water in a small pond to oscillate gently" with an amplitude of about two inches and a period of a few seconds. The description shows that the oscillation was a uninodal seiche, but neither the dimensions of the pond nor the period of the oscillation is given.[41] Forel cites this observation but justly concludes that the well known seiches of the Lake of Geneva were not due to earthquakes. Other writers have recognized the connection between earthquakes and disturbances of the waters, but they have not distinguished the progressive from the stationary waves, a distinction which is quite fundamental; nor have they explained how the disturbance is produced.

Our knowledge of seiches and of earthquakes has increased, and the agitation of the waters by the Lisbon earthquake can be shown in some cases, where the data are sufficient, to be true seiches; in other cases the data are only sufficient to show a probable seiche; and in still others no definite inference can be drawn at all.

The first and second preliminary tremors of an earthquake are both too fast and too weak to produce any marked effect on ponds or lakes at any considerable distance from the origin, and they claim no consideration here. But the large or surface waves have periods of from fifteen to twenty-five seconds, and even more, and have much larger amplitudes. By comparison with the California earthquake we can form some conception of the movement of the earth in northern Europe due to the Lisbon shock. The California earthquake was just sensible at a distance of three hundred miles, the Lisbon earthquakes at fifteen hundred miles; if we assume equality of periods in the waves, the amplitudes would be the same at these two distances respectively. At Carson City, near the limit of sensibility of the California earthquake, the amplitude of the movement was about one centimeter,[42] and the range twice as much; we may therefore consider that the range of movement in northern Europe due to the Lisbon earthquakes was about two cm. This reasoning is far from rigid, but I think we may feel reasonably satisfied that the range in northern Europe was between one and five cm. We must therefore determine if the natural periods of oscillation of the ponds, rivers, etc., lie between fifteen and twenty-five seconds, and synchronize with the period of the earthquake; if they do, the probable amplitude of the earth vibrations would undoubtedly be sufficient to set up true seiches.

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[40] Le Leman, 2, 200-211.

[41] *Nature*, 1889, 40, 162.

When we take into consideration the difference of longitude between Lisbon and Portsmouth, England, (8°), and the time for the large waves to travel the distance, (13°, or 3500 km.), we should expect the disturbance to begin there at 10:18 a.m. It was reported "about thirty-five minutes after ten." This is a satisfactory agreement for a general observation at a period when time was not kept with great accuracy, and where the information was collected several weeks after the event. The following is the account of the agitation:[43]

"On Saturday, November 1, 1755, about thirty-five minutes after ten in the morning, there was observed in the dock-yard at Portsmouth an extraordinary motion of the waters in the north dock, and in the bason and at two of the jetty heads.

"In the north dock, whose length is about 229 feet, breadth 74 feet, and at that time about 16½ feet depth of water, shut in by a pair of strong gates, well secured, his Majesty's ship the Gosport, of forty guns, was just let in to be dock'd and well stay'd by guys and hawsers (certain large ropes, so called). On a sudden the ship ran backwards near three feet, and then forwards as much, and at the same time she alternately pitch'd with her stern and head to the depth of near three feet; and, by the liberation of the water, the gates alternately opened and shut, receding from one another near four inches.

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[42] "California Earthquake Report," 2, 136.

[43] *Phil. Trans.*, 1755, 49, 351-353.

"In the bason, whose length is about 240 feet, breadth 220 feet, and at that time about 17 feet depth of water, shut in by two pair of gates, lay the Berwick, of 70 guns, the Dover, of 40 guns, both in a direction nearly parallel to the Gosport; and a merchant ship of about six hundred tons, unloading of tar, lying in an oblique direction to the others. These ships were observed to be agitated in like manner with the Gosport, and the tar ship to roll from side to side. The swell of the water against the sides of the bason was observed to be nine inches; one of the workmen measured it between the librations.

"The Nassau, a seventy gun ship, lying along-side a jetty head between the north dock and the bason; also the Duke, a ninety gun ship, lying against the next jetty-head, to the southward, both in a direction nearly at right angles to the others, were observed to be rock'd in the same manner, but not quite so violently. These two ships lay in the harbor."

The period of the uninodal, or fundamental seiche of the basin, can be calculated with sufficient accuracy from the formula,

$$T = 2l/\sqrt{gh},$$

where T is the period, l the length of the pond, h its depth, and g the acceleration of gravity. We find 20½ seconds for the period of the basin, and 19½ for the north dock. These are near enough to the period of the earthquake vibrations to produce true seiches.

The water of a pond five miles from Dunham[44] rose and fell several inches for six or seven minutes, at the rate of four or five oscillations a minute. The pond was 40 yards long and 10 wide. If we assume an average depth of 4 feet, we find a natural period of 21 seconds. If the pond were 6 feet deep the period would have been 17 seconds. The rough estimate of the frequency is in satisfactory agreement with the calculated period.

At Busbridge, Surrey, there was a canal nearly 700 feet long and 58 feet wide, running about east and west. The water was usually from 2 to 4 feet deep at the eastern end, gradually increasing to about

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[44] Same, 385.

10 feet at the western end. The banks were evidently sloping. About 10:30 in the morning the attention of two gardeners was attracted to the canal by a noise in the water; the following account was obtained from them:[45]

"The water soon raised itself in a heap or ridge, extending lengthwise about thirty yards, and between two or three feet above the usual level of the water; after which the heap or ridge heeled or vibrated towards the north . . . On the water's returning back into the canal, it again raised itself into a heap or ridge in the middle; after which the heap or ridge heeled or vibrated with greater force towards the south . . . and flowed over the grass walk.

"During this latter motion the bottom of the canal, on the north side, for several feet in width, was quite bare of water."

The disturbance continued for about fifteen minutes; it was confined to the eastern end of the canal where the water "usually pens from two to four feet," and no motion was noticed in the western end "where it pens to about ten feet." This seems to be, with some exaggeration, the description of a seiche changed, near the shore, into a progressive wave by the sloping shape of the bank. A modification may also have been caused by the shallowness of the water. To calculate the period we must take a depth somewhat less than the average depth of the section; with an assumed effective average depth of 1½ feet for the eastern end of the canal, we get a period of about 17 seconds; with an average depth of 2 feet, we should find a period of 14½ seconds. Assuming an average depth of 5 feet for the deep end of the canal, we find a natural period there about 9 seconds; evidently too short to respond to the earthquake waves. This is a very instructive case, showing clearly the presence of sympathetic oscillations at one end of the canal, and their absence at the other, the difference being due to the natural periods at the two ends.

There are other cases of this selective action. At Peerless Pool, London,[46] there were three bodies of water spoken of as the "fishpond," the "pleasure bath," and the "cold bath;" the first two were much agitated; the third, lying between them, was not. At Rockford in Essex,[47] the water of a large round pond was oscillated uninodally in an east-west direction; whereas two neighboring ponds, long in a north-south direction and very narrow east-west, remained perfectly quiet. The movement lasted for about fifteen minutes. A pond in Hertfordshire,[48] about 130 feet wide and 200 feet long, was agitated in a north-south direction (probably the shorter breadth); whereas another pond, separated from it merely by a roadway, and of about the same size, but with an island in the center, showed no disturbance whatever. If we assume a depth of 6 feet, the period of oscillation along the shorter breadth would be 19 seconds. The island in the other pond breaks it up, so that its period must have been too short to respond to the earthquake vibrations.

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[45] Same, 354.

[46] Same, 363.

[47] Same, 364.

There are two cases in which binodal seiches are described. Viscount Parker, F.R.S., had his attention called to the disturbance of the water at the southwest corner of the moat around Shirburn Castle, Oxfordshire.[49] He writes:

"There was a pretty thick fog, not a breath of air, and the surface of the water all over the moat was as smooth as a looking-glass: notwithstanding which, in the corner of the moat near which I stood, the water flowed into the shore, and retired again successively, in a surprising manner. How long it had done so before I came, or in what manner it began to move, I cannot tell. The flux and reflux, when I saw it, were quite regular. Every flood began gently; its velocity increased by degrees, till at last, with great impetuosity, it rushed in till it had reached its full height, at which it remained for a little while, and then again retired, at first gently ebbing, at last sinking away with such quickness that it left a considerable quantity of water entangled amongst the pebbles, laid to defend the bank, which run thence in little streams over the shore, now deserted by the water, which at other times always covers it. As the slope of the sides of the moat is very gentle, the space left by the water at its reflux was considerable, though the difference between the highest flood and lowest ebb of these little tides, if I may be allowed the expression, was but about four inches and a half perpendicular height; the whole body of water seeming to be violently thrown against the bank, and then retiring again, while the surface of the whole moat all the time continued quite smooth, without even the least wrinkle of a wave. The time it took up in one flux and reflux, as I did not then observe it, I cannot pretend to guess at. There happened to lie at the bottom of the water, about four feet deep as I believe, several pieces of white paper; and I could perceive them move backward and forward, keeping pace with some weeds and other things, which floated on the top of the water backward and forward, as it ebb'd and flow'd. Being desirous to know whether the motion was universal over the moat, I sent a person to the other corner of it, at the same end that I stood, and about twenty-five yards from me, to examine whether the water moved there or not. He could perceive no motion there, or hardly any; but another, who went to the northeast corner of the moat, diagonally opposite to me, found it as considerable as where I was. As I imagined that in all probability the water at the corner diagonally opposite to that where I stood would sink, as that by me rose, I ordered him to signify to me, calling out, when the water by him began to sink, and when to rise." It was found that the water rose and fell synchronously at these two opposite corners, which were ninety or a hundred yards apart. Viscount Parker then sent a man to a pond about forty yards distant, where the waters were somewhat similarly agitated, but he found that the period was a little faster than in the moat. Other ponds nearby were also affected. The duration of the disturbance was not noted, but a half hour later all was quiet.

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[48] Same, 684-685.

[49] Same, 368-370.

A binodal seiche is clearly indicated in the moat; no progressive waves were seen, except the rushing of the water up and down the sloping bank; there were marked synchronous movements at the opposite corners, about a hundred yards apart, and there was quiet (*i. e.*, a node) at a point twenty-five yards, or one quarter of the length, from one end. If we calculate the average depth of the cross-section of the moat necessary to have a binodal period of about twenty seconds, we find seven feet, which is about what one would expect the depth of a moat to be.[50] The moat and pond must have been set in oscillation with the period of the earthquake waves, but when the disturbance passed away they would fall back into their proper periods, which must have differed but slightly from the period of the earthquake waves and also from each other; it must have been in this phase of the phenomenon that the movements in the pond and in the moat were compared.

A binodal seiche is apparently also described in the following account. At a pond at Eaton-bridge[51] crossed by a post and rail, some people "saw the water open in the middle so that they could see the post and rail a good way down, almost to the bottom, and the water dashing up over a bank about two feet high, and perpendicular to the pond. They did not feel the least motion upon the shore, nor was there any wind, but a dead calm."

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[50] The depth of four feet mentioned by the Viscount referred apparently to the shallower water near the shore.

[51] Same, 360, 361.

Accounts of the disturbance in many other ponds are found in the *Philosophical Transactions,* but with details insufficient to estimate their approximate periods of oscillation. Backward and forward swinging movements of the waters are described, clearly indicating uninodal seiches. The agitation seems to have lasted ten or fifteen minutes; in some ponds the oscillations were north-south, in others east-west. The waters were in some cases said to boil, which may have been due to irregularities as the seiches were being set up; and this may also be the explanation of the rushing noises reported, which seem first to have drawn the attention of the observers to the phenomenon. The stirring up of mud shows that all the water of the ponds was involved, and that superficial waves were not the cause of the disturbance.

Oscillations appeared in the Thames River between 11 and 12 o'clock; the waves being like those caused by the launching of a ship, which indicates a period of some seconds; after three or four elevations of the water, the movement gradually subsided.[52] In Yarmouth haven and at Hull, on the east coast of England, a little before noon, "the water rose five or six feet, and fell again in a minute or two." [53] This seems an exaggerated and unsatisfactory account of a seiche; the time shows it could not be due to the sea-waves.

On the continent similar oscillations occurred: in Holland, for instance, at the Hague, at Leyden, Haarlem, Amsterdam, Gonda, Utrecht, Rotterdam, and Brisledue.[54] At Leyden the vertical movement was about one foot; the time was 11 o'clock. Woerle [55] looks upon these disturbances as due to sea-waves; but these places are not on the coast, but on rivers and canals, which would probably have about the proper natural period of oscillation. Moreover, the agitations occurred about the time the Lisbon shock would have reached the various localities; and this excludes the sea-waves as a cause, for they could not have reached the Holland coast before the next morning.

Oscillations also occurred in the basin at Havre, and in some ponds in the general neighborhood, and in many rivers and ponds throughout northern Europe.[56] It is not necessary to catalog them here; they were comparatively small, and apparently of about the right dimensions for seiches to be set up in them by the earthquake vibrations; moreover the times, when given, correspond to the time of arrival of the earthquake disturbance. The Aurasoki River, at Åbo, Finland, is the most distant point of which we have credible reports of oscillations. Its distance from the origin is 31½°, or 3500 km., and the time of the agitation is given as 12 noon, within a minute of the calculated time of arrival of the long earthquake waves. Woerle classes the agitation at Åbo with the sea-waves, but the latter would have taken a day or two longer to reach there.

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[52] Same, 361.

[53] Same, 380, 381.

[54] Same, 396-398.

[55] Woerle, 67, 68.

[56] Same, 70-77.

Some lakes were agitated that were so large that their uninodal or binodal periods would be much longer than the period of the earthquake waves. Multinodal seiches may have been set up; or what seems more probable, seiches confined to a small bay, or to a shelving shore, may have been developed. That the latter kind, or *open* seiches, as they may be called, are not only possible, but common, has been made evident by the work in Japan under the direction of Nagaoka,[57] and by that of Harris.[58] These seiches are analogous to the vibrations of a closed organ-pipe, the closed end of the pipe corresponding to the shore and the mouth of the pipe to the mouth of the bay, or to the place where the depth changes rapidly. Seiches of this character could be generated either by waves at the mouth of the bay or by a shaking of the shore. Open seiches with periods as small as twenty seconds have not been described; but they might be found if they were especially looked for. Limnographs are usually not adjusted to record them. Forel describes what he calls "vibrations" of the lake, which resemble seiches with periods of from fifteen to one hundred and twenty seconds. He thought they were almost always present, and was inclined to look upon them as multinodal seiches.[59] It is quite possible that they were open seiches. Two causes may have caused Forel's failure to record seiches, due to earthquakes: his instrument may at the time not have been adjusted to record seiches with a period as short as twenty seconds; and no large earthquakes occurred during his observations which could have had long-period earth-waves of sufficiently large amplitudes at the Lake of Geneva.

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[57] "The Secondary Undulations of Oceanic Tides," *Pub. E. Q. Invest. Com. in For. Lang.*, No. 26, Tokio, 1908. Omori seems first to have recognized the existence of seiches in open bays.

[58] "A Manual of Tides," Part V, chap. ix, Rep. U. S. Coast and Geod. Survey, 1907.

[59] Le Léman, 2, 213-224.

It is to open seiches that I would refer the agitation on the shores of large lakes at the time of the Lisbon earthquake. Unfortunately, the accounts of the agitation are too incomplete to confirm or to contradict this idea; in most cases the agitation was only reported from one or two points of a particular lake, and we do not know whether the other parts of the lake were affected or not. In Great Britain we have reports from Windermere, Coniston Water, Esthwaite Water, Loch Ness and Loch Katrine, generally with the statement that there was no wind, but with insufficient detail to enable us to estimate the period.[60] These bodies of water are much too large for their uninodal periods to approach the period of the earthquake waves. At Queen's Ferry, near Edinburgh, on the Firth of Forth, about 10 o'clock in the morning, the water rose and fell about a foot or eighteen inches, "which made the barks and boats then afloat run forwards and backwards on their ropes with great rapidity; and this continued for three or four minutes, it being calm; but after the second or third rush of water it always grew less." [61] This indicates a number of oscillations within a few minutes. A similar agitation apparently occurred at Alloa, at the head of the Firth, but nowhere else on its shores. The account of Loch Lomond differs materially from the others.[62] One Angus M'Diarmid, an inn-keeper, observed the movement of the water with his watch in his hand. Beginning at half-past nine, the water rose and fell two feet four inches with a period of ten minutes, and in perfectly calm weather. The disturbance began to subside at fifteen minutes after ten, and by eleven all was quiet again. Chrystal, in his "Hydrodynamical Theory of Seiches," reprints a similar account of this disturbance from the *Scots Magazine* of 1755, and considers it a true seiche produced by the Lisbon earthquake, but is unable to explain how it was caused.[63] It certainly seems impossible that a seiche with a period of ten minutes could be produced by the far more rapid vibrations of the earthquake; and if the apparent accuracy of the observations at Loch Lomond is real, the seiche there must have owed its origin to some other cause; for the long earthquake waves could not have reached Loch Lomond before 10:15, three quarters of an hour after the disturbance is reported to have begun.

During Chrystal's observations at Loch Earn, an earthquake occurred with its center about twenty miles to the southeast; the intensity at the center was between VI and VII, R-F, and Loch Earn lay three or four miles outside of isoseismal IV.[64] No seiche was generated in the lake. As the estimated duration of the shock was only 3.4 seconds, the vibrations must have been much too rapid to produce a seiche.

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[60] *Phil. Trans.*, **49**, 381-384, 387-390.

[61] Same, 550-552.

[62] Same, 389-390.

[63] *Trans. R. S. Edin.*, 1904-5, **41**, Pt. III, 599; 1908-9, **46**, Pt. III, 468.

Many of the lakes in Italy, in the Alps, in Germany and in southern Scandinavia were disturbed by the Lisbon earthquake; also fiords in Norway. Some of the reports are wholly incredible, such as the statement that the earthquake "swelled our lake of Neuchatel to the height of near two feet above its natural level for the space of a few hours";[65] and in general the accounts as reproduced by Woerle are too summary for any definite inference.

This examination of the agitation of the inland waters leads to the conclusion that in many small bodies of water true seiches were produced by the earthquake vibrations, on account of synchronism of periods; that in other cases, such as the canals of Holland and the continental ponds and rivers, seiches were very probably set up in the same way; and that open seiches may have been generated in small parts of the larger lakes; and that there is no satisfactory evidence that the agitations of the inland waters by the earthquake were not always of the nature of seiches.[66]

Sea-waves.—The great waves generated in the ocean by the Lisbon earthquake were among the most striking of its effects. Woerle indicates on his maps that these waves washed the shores of the North Atlantic nearly over their whole extent in America and Europe, including the western Mediterranean, the North Sea and the Baltic. But this conclusion requires to be greatly modified; the sea-waves could not have reached the North Sea or the Baltic before November 2d, whereas the recorded times place the disturbance in these seas a few minutes after the earthquake, and thus throw them into the class of oscillations. We shall also learn that evidence of waves on the coast of North America is insufficient.

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[64] "The Ochil Earthquakes of September, 1900, to April, 1907." Charles Davison, *Quar. Jr. Geol. Soc.*, 1907, **63**, 362-374.

[65] *Phil. Trans.*, 1755, **49**, 436, 437.

[66] Woerle rejects the idea of seiches, because he considers them as necessarily due to meteorological agents. His suggestions that the Alpine lakes owed their agitation to a change in the form of their basins, that there was a subterranean connection between Lisbon and some German lakes, and that the lakes of the Baltic provinces and of England were especially affected because they were all in glaciated regions, need not detain us.

The interval between the shock and the arrival of the sea-waves at Lisbon has been variously given. Michell[67] estimates the interval at twelve minutes, and uses this value to determine the distance of the epicenter. Woerle thinks it was about an hour.[68] There seem to have been three large waves, reported to be from fifteen to forty feet high. The waves were much stronger south of Lisbon than north of it. At Cadiz they arrived one or two hours after the shock. They were very violent on the northwest shore of Africa. At Madeira the waves arrived about two hours after the shock, and rose about fifteen feet above high-water mark.[69] In the Canary Islands similar phenomena were seen; also in the Azores, where the waves were very strong. At Madeira it is clear that the water first withdrew and then advanced; and Woerle concludes from evidence which is not before me that it also first withdrew at Lisbon and at Cadiz, but first advanced along other parts of the Portuguese coast. The waves must have entered the Mediterranean at Gibraltar, but would naturally die out in a short distance. They were reported at the Balearic Islands and at Sardinia, but the evidence is contradictory.[70]

The waves reached the southwest coast of England not long after 2 p.m. on November 1st, the disturbance beginning with an elevation and an inrush of the water like an extraordinary tide. The water rose and sank vertically over a range varying in different places from six to ten feet. Near Plymouth the disturbance began about 4 p.m. and lasted more than a half hour; the period seems to have been about ten minutes. At Mounts Bay the disturbance began soon after two and lasted for five and one-half hours, with a period of about twenty minutes. The waves passed into St. George's Channel and Bristol Channel and arrived at the more distant points at successively later times.[71] At Kingsale, on the southern coast of Ireland, a little west of Cork, the water rose and fell five and one-half feet between 2 and 3 p.m. There are two accounts of this occurrence, both written from Kingsale; one says: "It is reported that, about nine o'clock in the morning, a shock of an earthquake was felt at Cork; but I have not met any persons of credit who pretend to say they felt it." This letter was dated December 7th. The second letter was dated November 2d, and says: "There was a violent shock of an earthquake felt yesterday at Cork, and at the same moment of time we had a most surprising thing happen here," and then goes on to describe the disturbance of the water.[72] We infer that the shock was slightly felt in Cork about nine in the morning, and that an indefinite and exaggerated rumor of it had reached the writer of the second letter, and he unjustifiably assumed that the two phenomena took place at the same time. There is an account of the agitation of the waters at Dartmouth, which is put at 9 a.m.; but this account was written six months later, and has probably confused the times.[73] There are no other accounts in the *Philosophical Transactions* of true sea-waves on the English coast on November 1, 1755.

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[67] Loc. cit., 67.

[68] See also *Phil. Trans.*, 1755, **49**, 411-413.

[69] Same, 425-436.

[70] Woerle, 39-46.

[71] *Phil. Trans.*, 1755, **49**, 371-379.

Captain Affleck, commanding the Advice man-of-war, wrote from Antigua on January 3, 1756: "The year was usher'd in here by the shocks of an earthquake, which is the second which I have felt at this island; neither of which have been violent enough to do any damage. On the 1st of November last, I find you had a remarkably sudden flux and reflux of the sea at Portsmouth and other parts of the coast, which [the sea] was agitated in like manner, at the same time, on the coast of America, and all these islands. The tide here rose twelve feet perpendicular several times; . . . it began at half an hour after three in the afternoon . . . and flowed every five minutes, five feet perpendicular, till as much after six. . . ."[74] He mentions in particular the islands of Martinique, Barbadoes, St. Martin's and Sabia. This seems to be the only evidence that the waves were noticed on the American continent; and it certainly is not satisfactory. It is possible that the opening passage of Captain Affleck's letter may have been misinterpreted to refer to the date of the Lisbon earthquake, and may have given rise to the belief that that shock was felt in the West Indies.

We conclude that the sea-waves washed the shores of southwestern Europe, northwestern Africa, southern England and Ireland, and the West Indies; that they may have appeared in the western part of the Mediterranean; but that there is no evidence that they entered the North Sea or the Baltic and only a hint that they were observed on the coast of America. These waves must have been generated near the origin of the earthquake; they were propagated as ordinary long water-waves with speeds dependent upon the depths of the ocean. The times of their arrival at distant places correspond satisfactorily with the time calculated according to Airy's formula for the speed of propagation of long waves. The periods noticed in the different harbors were not the periods of the waves in the open sea, but must be looked upon as characteristic of open seiches in the various harbors; for the periods were quite different at different places.

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[72] Same, 391-394.

[73] Same, 643.

[74] Same, 668-670.

The Lisbon earthquake still remains the most notable earthquake in history; it impressed on the world in a most effective way the great phenomena of earthquakes, terrestrial and marine. Woerle has done good service in collecting and examining the greater part of the contemporary records; the Spanish and Portuguese records, however, remain unexplored. A severely critical examination of all the early records, would, I think, bring out some important characteristics of this great shock. No attempt has been made in this article to do more than to correct some very exaggerated traditions, and to apply our present knowledge of earthquakes to some phenomena not heretofore explained.

AREQUIPA EARTHQUAKES REGISTERED DURING THE YEAR 1913

By LEON CAMPBELL
Arequipa station of the Harvard College Observatory.
Communicated by the Director, Edward C. Pickering.

Earth tremors during 1913 only slightly exceeded those of 1912 in number, but they were decidedly stronger in intensity. Especially so the one of August 6th, to which special reference is made in the remarks following table I.

It has often been suggested that earthquakes were considerably stronger in the city of Arequipa than at the Observatory, some three miles distant, and accordingly Mr. F. J. Brett, of the Arequipa English School, has been kind enough to keep a record of those felt by him in the city, using the same scale of intensities, the Rossi-Forel, that is used at the Observatory. Although the times do not agree so very closely, doubtless this is due more to the lack of an accurate knowledge of his watch error, than to any real difference in the time of transit of the shocks from one place to the other.

Eight earthquakes were recorded simultaneously in the two places, and the means of the observed intensities indicate only a slightly greater strength in favor of those noted in the city. The difference is so small, only 0.4 of a unit, that this is not very conclusive evidence, and it may be due to personal equation in the matter of judging the intensity.

In table I is given a list of the earthquakes as registered in the two places. Column 1 contains the current number assigned to each earthquake consecutively, while columns 2 and 3 give the date and time of each shock. Those recorded at the Observatory are doubtless accurately determined, since a watch comparison was usually made with the standard chronometer each time. For those recorded in the town only, probably a little uncertainty may occur. Column 4 contains the observed intensities at the Observatory, as made by the several members of the staff; while column 5 gives those observed by Mr. Brett. The last column contains the remarks made at the time of observation, or from subsequent knowledge which came to hand.

TABLE I.

AREQUIPA EARTHQUAKES DURING THE YEAR 1913.

No.	Date	75th Mer. Time	Intensity		Remarks
	1913	H. M. S.	Obs.	Town	
1	Jan. 20	11:52:00 p.m.	III		Duration 5 seconds.
2	Feb. 4	8:00 a.m.	II		Slight jar to the house.
3	Feb. 6	10:16:16 a.m.	I or II	III	Duration 15 seconds.
4	Mar. 8	7:56 a.m.	III	IV	Shock felt by several persons at rest. Even stronger in the town.
5	Mar. 21	5:50:20 a.m.	IV		Series of shocks, light, but lasting for 60 seconds. Jupiter seen to dance in field of telescope.
6	Mar. 23	8:56:23 a.m.	III		Duration 4 seconds.
7	Mar. 24	3:40 a.m.	II		Noted by two observers, lasting for 20 seconds, but seismoscope was not disturbed.
8	Mar. 30	10:15 p.m.		III	Duration 15 seconds.
9	Apr. 13	7:39 p.m.	II		Mark on the plate slightly changed to the SW.
10	May 24	11:48 a.m.		III	
11	May 25	11:34:32 a.m.	I		
12	June 12	11:00 a.m.	III		Mark on plate altered 2 mm. to SW. Double tremor noted by several observers.
13	July 13	7:11:20 a.m.	III		Felt by persons at rest; duration 3 seconds.
14	July 28	12:40:03 a.m.	VI	VI	Heavy series of shocks lasting for 70 seconds, felt by all those asleep. Secondary shock felt at 12:41:23 a.m. Needle-point seemed to be in motion as seismoscope house was entered, at 12:46:13 a.m. Mark on the plate rather extensive. Shock not very jolty, but continuous. Some clock pendulums were stopped. General alarm felt in the town. Cable companies report serious damage to cable lines off the coast of Peru, probably more of a seaquake than an earthquake.
15	July 28	11:00 p.m.		III	Reported in town only; duration 2 minutes.
16	Aug. 2	9:45 p.m.	III		Duration 10 seconds.
17	Aug. 6	5:14:07 p.m.	VIII	IX	The great earthquake of the year. See special remarks below.

No.	Date 1913	75th Mer. Time H. M. S.	Intensity Obs.	Intensity Town	Remarks
18	Aug. 6	5:27:57 p.m.	II		A tremendous earth-rumbling preceded the shock by a few seconds, similar to that of heavy cannonading.
19	Aug. 6	7:09:00 p.m.	II		Felt by persons at rest.
20	Aug. 6	9:11:26 p.m.	III		
21	Aug. 6	10:14 p.m.		III	
22	Aug. 6	10:44 p.m.		III	
23	Aug. 7	8:00 a.m.	II		
24	Aug. 8	12:23:42 p.m.	II		Bells ringing some 12 seconds later.
25	Aug. 12	9:17 p.m.	II		Felt only by persons at rest.
26	Aug. 12	9:19 p.m.	II		El Misti thought to be smoking.
27	Aug. 15	5:22 a.m.	III		Duration 20 seconds.
28	Aug. 15	6:39:30 a.m.	III		Duration 45 seconds.
29	Aug. 17	11:50:19 p.m.	IV		Duration 25 seconds, strong enough to awaken some persons.
30	Aug. 18	2:21:13 a.m.	III		Duration 12 seconds, slight movement of house.
31	Aug. 21	7:31:50 a.m.	II		Duration about 10 seconds.
32	Aug. 22	12:19:20 a.m.	II		Noted by only one observer.
33	Aug. 24	5:41:44 p.m.	I or II		
34	Sept. 1	7:53:04 p.m.	V	IV or V	Two distinct shocks, sudden, short, and strong, felt by all; separated by about 3 seconds.
35	Sept. 5	9:56:25 a.m.	III		Duration 15 seconds.
36	Sept. 7	10:53 a.m.	III		
37	Sept. 8	7:31:25 a.m.	III		Short, quick jolt, followed 20 seconds later by another equally strong.
38	Sept. 9	8:04:52 p.m.	III		Duration 30 seconds.
39	Sept. 11	8:15:15 a.m.	II		
40	Sept. 12	12:40 p.m.	I		
41	Sept. 19	1:16:27 p.m.	I		
42	Sept. 29	10:59:46 p.m.	III	III or IV	Windows rattled; rumbling heard 20 seconds before the shock arrived. Mark on the plate changed 2 mm. to SE. Duration 30 seconds.
43	Oct. 14	1:33:25 a.m.	V	IV	Heavy jolt, followed 50 seconds later by another. Mark on the plate changed 6 mm. in an E-W direction.
44	Oct. 14	6:50 a.m.	III		
45	Oct. 16	8:37:50 a.m.	III or IV	III	Felt as a severe jolt. Approach noted 15 seconds before the jolt, and in an E-W direction. Duration 20 seconds.
46	Oct. 16	11:28:30 a.m.	II		
47	Oct. 17	7:19:30 a.m.	I		
48	Oct. 17	11:03:30 a.m.	II		
49	Oct. 25	9:32:30 a.m.	II		
50	Nov. 4	4:47:50 a.m.	III	III or IV	Duration 30 seconds. Strong enough to awaken some persons.

No.	Date 1913	75th Mer. Time H. M. S.	Intensity Obs.	Intensity Town	Remarks
51	Nov. 5	9:30 p.m.		III	Duration 20 seconds.
52	Nov. 10	5:26:40 a.m.		IV	Duration 40 seconds; direction E-W.
53	Nov. 20	11:13:15 p.m.	III		Mark moved 2 mm. to S.
54	Dec. 1	7:18:40 a.m.	II		Mark moved 2 mm. to SE.
55	Dec. 4	7:25 p.m.	III		Mark moved slightly to S.
56	Dec. 10	1:00 a.m.	III		Duration 25 seconds. Awoke one observer only.
57	Dec. 23	5:26:00 a.m.	III		Duration 15 seconds.
58	Dec. 24	1:06:20 a.m.	V		Strong enough to awaken several observers; lasted 1 m. 49 s.; felt as three distinct shocks.

Special note on earthquake of August 6, 1913.—This earthquake occurred at 5:14:07 p.m., fortunately at a time when people were awake, and exits from buildings were easy. This was the strongest earthquake felt in Arequipa since 1883. At the the Observatory it was recorded as of intensity VIII, while in the city proper it could be called IX. Its duration was over three minutes, and the mark on the smoked-glass plate covered the entire surface. Great clouds of dust arose from the lava quarries at the base of the mountains, and the earth rocked continuously and strongly in an E-W direction. Some people complained of being very dizzy.

The populace was greatly alarmed, and some old houses were thrown down in the city. The tower of La Compania church was badly cracked, as well as the southeast corner of the portales in the main plaza. Numerous houses suffered great cracks, and were rendered unsafe. The heavy rumbling which preceded the shocks at 5:27 p.m. caused even greater consternation, and few people slept in their houses that night, for fear that another and more serious earthquake would follow. Later several houses, that had been damaged, collapsed.

Requests were sent to numerous places for authoritative data, but few answers of real value were received. At Mollendo, the port of Arequipa, replies received indicated that the intensity was slightly less than in Arequipa, probably VII. The manager of the Callyoma mines reported an intensity of about VI. At Tirapata, to the northeast of Arequipa, it was V or VI. At Puno, on the borders of Lake Titicaca, it was light, doubtless only III. At Cuzco, from newspaper reports only, it was classed as IV or V. The center of the shock appears to have been at, or near, Chuquibamba, about sixty miles west of Arequipa. It was at this place, according to government reports, of the greatest intensity, IX or X, since most lives were lost, and many houses destroyed, and large openings occurred in the earth's surface. It appears to have been nearly as strong at Camana. The shock was very generally felt all over the western part of Peru, on one side of the Andes. Reports from several persons who were then on the eastern side of the Andes indicate that no earthquake of any moment was noticed. The chief engineer of the Southern Railway reports that the earthquake was felt along the whole line of the railway, being strongest between Mollendo and Arequipa, and less intense towards Cuzco and Puno; which well confirms the other reports mentioned above. Had Arequipa not been so well built to withstand earthquakes, doubtless much more damage would have occurred.

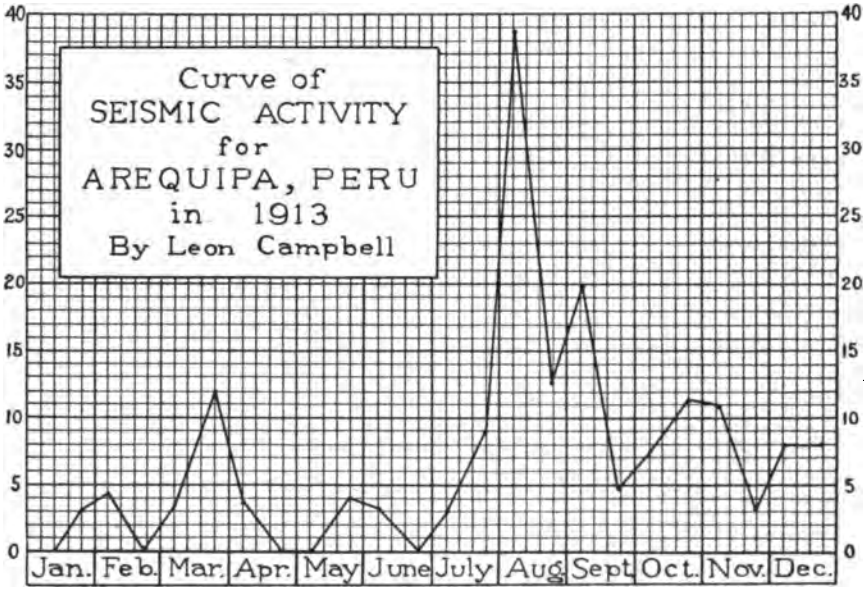

Fig. 1.

The extent of seismic activity in Arequipa is well shown in table I and figure 1. Semi-monthly values were derived of the number of earthquakes and the sums of their intensities, as taken from columns 1, and 4 and 5, of table I. Where the same disturbance was noted at both stations, the means of both estimates of intensity were used. Column 1 of table II contains the including dates of each half-month. while columns 2 and 3 give the sum total of the earthquakes in that interval of time, and the sum of the intensities of the same.

TABLE II

TABLE OF SEISMIC ACTIVITY IN AREQUIPA, 1913

Dates 1913	No. of earthquakes	Sum of intensities	Dates 1913	No. of earthquakes	Sum of intensities
Jan. 1-15	0	0.0	July 1-15	1	3.0
16-31	1	3.0	16-31	2	9.0
Feb. 1-14	2	4.5	Aug. 1-15	13	39.5
15-28	0	0.0	16-31	5	12.5
Mar. 1-15	1	3.5	Sept. 1-15	7	19.8
16-31	4	12.0	16-30	2	4.5
Apr. 1-15	1	3.5	Oct. 1-15	2	7.5
16-30	0	0.0	16-31	5	11.5
May 1-15	0	0.0	Nov. 1-15	3	10.8
16-31	2	4.0	16-30	1	3.0
Jun. 1-15	1	3.0	Dec. 1-15	3	8.0
16-30	0	0.0	16-31	2	8.0

A glance at figure 1 will show the rather quiet condition of the earth before the latter part of July, except for the small rise in activity about the latter part of March. After the earthquake of August 6th

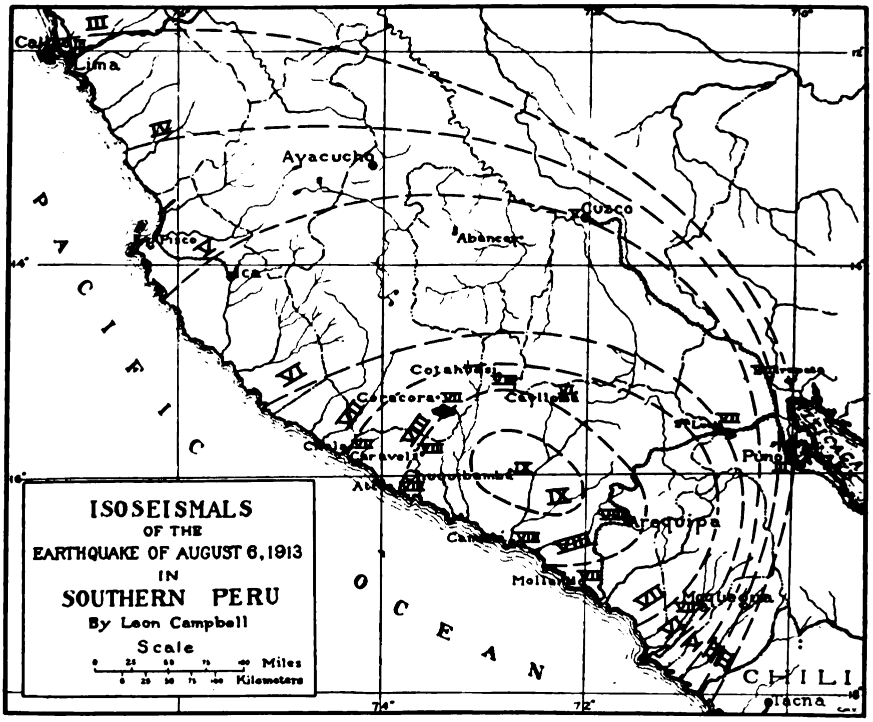

Fig. 2.

the earth gradually quieted down, although not very promptly, as we should expect. The rise in the curve early in November recalls that in the valley of Aymares, due northwest of Arequipa about one hundred and twenty miles, occurred a very severe earthquake on November 7th. Curiously enough no disturbances were noted in Arequipa on this date. The severe earthquakes at Aymares may be somewhat allied to that of August 5th, since this region lies only just the other side of a mountain range close to Cotahusi and Chuquibamba, but not enough data are at hand to decide definitely. In all, 1913 appears to have been one of the most interesting, from a seismological standpoint, in recent years.

Figure 2 represents the isoseismal chart of the earthquake of August 6th, and also shows the valley of Aymares, where occurred the disturbances of November 7th.

SEISMOLOGICAL NOTES

Santa Cruz, California.—On March 13, 1914, at 11:40 p.m., a shock with an intensity of IV, R.F. scale, was felt at Santa Cruz, California. Another, but feeble shock (III, R.F. scale) was felt at 4:20 a.m. on March 18th. These shocks were kindly reported by David C. Moore.

San Jose, California.—Mr. H. A. Chapin reports a shock at San Jose, California, at 3:30 a.m. on March 18, 1914.

Stanford University, California.—Professor W. F. Durand reports a slight shock on March 18th at 10:45 p.m. It was barely perceptible. On the 19th he observed a similar shock at 4:30 a.m. that caused a creaking of his house.

Messina, Sicily.—On March 27, 1914, a sharp earthquake occurred at Messina. The inhabitants were panic stricken, and fled to the open country. No damage seems to have been done.

March 29, 1914.—Most of the seismographs of the United States and Canada recorded a distinct earthquake, beginning at Washington, at 7:48 p.m.

Martinique.—A sharp earthquake was felt at Fort de France, Martinique, April 17, 1914, at 7:30 a.m. There was much alarm, but no serious damage was done.

Reno, Nevada.—April 24, 1914, at 12:33 a.m., there was a sharp earthquake at Reno, Nevada. The people rushed into the streets, but no damage was done.

The Sicilian earthquakes of May 8-26.—The region southeast of Mt. Etna between Catania and Mangano was shaken by a severe earthquake on Friday night, May 8th.

The principal shock was preceded by slight tremors that had been occurring since April 25th, and there was a simultaneous renewal of volcanic activity by Mt. Etna.

The main shock of May 8th lasted six seconds, and about one hundred and sixty persons are said to have been killed and some three hundred injured. The village of Lanera, at or near the epicenter, was completely destroyed; while Santa Venerina, Cosentini, Bongiardo, Pisano, Passapomo, Pennisi, Trecastagni, Zerbati, and Zafferana were either destroyed or seriously damaged. Landslides were caused by the earthquake, and these seriously damaged the roads and the railway for more than a half mile between Acireale and Mandano.

The earthquake occurred while the people were still in the fields, and for that reason the mortality was not so great as it otherwise would have been. Most of the victims at Lanera were women and children.

The area seriously affected is only about three square miles. The church bells at Lanera were thrown a distance of five hundred feet. Outside of this area of high intensity the violence declined so rapidly that at Acireale, four miles from Lanera, there was but little damage done. It seems probable therefore that the focus of the principal disturbance was not deep seated.

The shocks continued to be felt for several days. Several were registered on the 11th, but no further damage was done. On the 15th several houses fell that had been weakened by the earlier shocks; and on the 26th these after-shocks were still reported as of daily occurrence. Mt. Etna continues active.

Everything possible was done by the government for the relief of the people.

Salt Lake City, Utah.—Our colleague, E. P. Jennings, of Salt Lake City, reports a slight shock in that place on May 14, 1914, at 10:15 a.m., with an intensity between III and IV of the R-F scale, and a duration of three seconds. The first shock was followed by a slighter one at 10:18 a.m. This earthquake was noted along the Wasatch fault-line from near the Idaho line to points thirty miles south of Salt Lake City, a distance of one hundred and forty miles. At Ogden some consternation was caused in tall buildings, and some large windows are reported to have been broken in that city.

Panama.—Severe shocks lasting more than thirty seconds, were felt at Panama and Colon, Canal Zone, at 10:25 p.m., on May 27, 1914.

No damage to the canal has been reported by the newspapers, but the shock seems to have been one of the strongest and longest recorded in the canal zone of late years. The people fled from their houses in alarm.

Our colleague, Mr. J. F. Brennan, reports that a shock, probably the same one, was felt at 10:30 p.m., at Kingston, Jamaica. The duration at Kingston was ten seconds, and the horizontal movement was 0.017 of an inch.

Sydney, N. S. W.—The seismograph at Riverview, Sydney, recorded a violent earthquake, May 28, 1914, at 11:30 a.m. The seismic waves lasted for three hours. The center of the disturbance seems to have been in the vicinity of Tonga Island, in the South Pacific Ocean.

Fairbanks, Alaska.—Several earthquakes accompanied by rumblings were felt at Fairbanks, Alaska, May 29, 1914. There were five distinct shocks in forty-eight hours, the more pronounced being at 6:03 a.m. These were the severest felt since the eruption of Katmai in June, 1912.

Guayaquil, Ecuador.—A heavy shock is reported at Guayaquil and Quito in Ecuador on the morning of June 1, 1914. Many houses were damaged and there was general alarm.

Volcanic eruptions in Java.—The following is the newspaper report of eruptions that occurred on Java on June 5, 1914: "A violent volcanic eruption occurred today on the Dutch Island of Sanguir, 140 miles south of Mindanao, in the Philippines. Several volcanoes were included in the disturbance.

"Streams of boiling lava poured down the sides of the mountains, overwhelming forests and cocoa plantations. At the same time a heavy rain of stones and ashes from various craters fell over the whole island.

"Official reports do not mention loss of life, but register the destruction of one hundred homes.

"Sanguir is the largest of the group known as the Talautz Islands, in the Celebes Sea, about five hundred miles to the east of British North Borneo. Destructive outbreaks of Gunong Abu, the principal volcano on the islands, occurred in 1711, 1812, 1883 and 1892."

Palo Alto, California.—An earthquake was observed by Professor D. M. Folsom, June 21st at 12:02 a.m. The shock lasted less than a second and the intensity was estimated as II, R.F. scale.

Redlands, California.—A shock lasting three seconds is reported from Redlands, June 25, 1914, but the exact time is not mentioned.

Sumatra.—A violent earthquake is reported in southern Sumatra, June 26, 1914, in which many persons were killed. At Bengkoelen buildings were destroyed and telegraphic communications were interrupted.

Volcanic activity of Lassen Peak, California.—Lassen Peak, a well known volcanic cone in the southeast corner of Shasta County, California, has shown signs of renewed activity since May 29th. Volumes of steam and volcanic dust were thrown high in the air. Subterranean rumblings are reported, and on May 31st slight earthquakes are said to have been felt at Hall's Flat, some twenty miles northeast of the peak. Renewed outbursts occur from time to time, and there are occasional showers of fragmental materials. One man was seriously hurt by falling stones. Ashes have fallen all over the peak, and at times a dark haze hangs about it. Although the high temperature has approached the surface in the crater, there seems to be no evidence as yet of a general rise elsewhere about the mountain. Dr. J. S. Diller of the U. S. Geological Survey has visited the peak since it has shown signs of renewed activity, and will soon report upon it.

Anyone who wishes to get a clear idea of the geology of the region should consult the Lassen Peak folio, no. 15, of the U. S. Geological Survey, by J. S. Diller, published at Washington in 1895.

On July 1st there was renewed activity, a dark mushroom-shaped cloud rose high above the peak, and ashes fell at Macomber Flats, thirteen miles away. Reports from the neighborhood of the peak suggest that the later disturbances are more violent than the earlier ones.

International Seismological Association.—Prince Galitzin will preside over the fifth meeting of the International Seismological Association, to be held early next September, in St. Petersburg. The exact date of the meeting is not yet fixed, but the provisional programme has just been issued. Reports will be presented by the committees on microseisms, on tides in the earth's crust, the bibliography of seismology, the catalogues of earthquakes prepared by the permanent committee, and the uniformity in the arrangement of seismological bulletins. It will be proposed that a new station shall be founded at Bergen, that a reserve supply of seismographs should be kept for occasional or temporary use, and it will be urged that all seismographs should be provided with suitable "damping" arrangements, and that correct time should be supplied by telegraphic signals to all earthquake observatories. Among the papers promised may be mentioned those of the president on the analysis of seismograms, the comparative study of seismograms of different stations, and on observations of the angle of emergence, and of Professor Omori on the tromometric observations made during the recent eruptions on the flanks of the Sama-yama. —*Nature*, 93, 168.

REVIEWS

SEISMOLOGY.—*Publications of the St. Louis University,* vol. X, no. 1, pp. 1-61. April 1914.

This number of the bulletin from the geophysical observatory contains an interesting discussion of the "Epicenter Problem" and a lecture on "Seismology and the Seismograph" by Professor J. B. Macelwane, professor of physics in the St. Louis University.

The first of these articles is divided into two papers. In one is given the method of approximating the epicenter of an earthquake when the arrival times of the preliminary tremors *P* at one or more sets of these selected stations are known. The Laufzeitkurve No. 2 of Wiechert and Zoeppritz, called the "W & Z curve," is the basis of the charts used. By means of these charts and by comparison of the time of arrival of the *P*-tremor at other stations, as given by the Shide bulletins, the epicenter can be at once graphically located.

A time difference chart for the stations at Berkeley, Ottawa and St. Louis, and another for St. Louis, Ottawa and New Orleans, illustrate the application of this method to the American continent; while for Europe is given a chart for the stations at Hamburg, Vienna and Pulkowa.

Obviously this method presupposes reliable and accurate time observations; but if two or more sets of three stations report time of arrivals, it is possible to check against an error in any one of the stations. Examples are given of the location of some epicenters in the order in which they were made at the St. Louis station.

In the second paper is developed and discussed a set of formulæ for use with time difference charts where there may be only a rough determination of the arrival of the *P*-tremor. These formulæ are believed by the authors to be original,—at least no reference to them could be found in the seismological literature. They are described as parametric equations of the time difference loci, and of all sorts of cognate loci. In deducing these formulæ the transfer time was made the independent variable, instead of the transfer distance, as seems hitherto to have been done in attempts to derive suitable expressions for use in interpreting seismological records.

Professor Macelwane in his lecture commented on the youth of the science of seismology, and sketched the development of knowledge in regard to earthquakes after the work of Professor Suess in 1872 on the Calabrian and Austrian series of earthquakes had refuted the centrum theory accepted since the time of Aristotle.

The experiments of Hobbs and Reid are described, as well as the movements along the fault-line of the California earthquake. Professor von Rebeur-Paschwitz is given credit for ushering in a new era in the history of earthquake science, when in 1894 he discovered that his delicate pendulums were disturbed by earthquakes on the other side of the planet. Since that time nearly three hundred seismograph stations have been established, and the observations carefully recorded.

The different types of seismographs are briefly described in the lecture, and the interpretation of the charts discussed.

The bulletin also contains a complete record of the St. Louis earthquake station for 1913.

D. M. Folsom.

Die Internationale Zeitkonferenz zu Paris im Oktober, 1912, von O. Hecker. *Mitteilungen des Zentralbureaus der Seismologischen Assoziation,* Nr. 1, 1-5, 1914. (*Beiträge zur Geophysik,* **13,** *Beil. Mittl. zu Heft 1.*)

In this report of the international time conference, the desirability of time uniformity obtained by means of wireless time-signals is emphasized. It is recommended: (1) that Greenwich time be used the world over, (2) that an international time committee be formed, and (3) that an international time station be established in Paris. There are also many detailed recommendations as to time-signals, etc.

A. F. Rogers.

Absorption und Fortpflanzungsgeschwindigkeit der Hauptbebenwellen, by W. Pechau. *Beiträge zur Geophysik,* **13,** 205-216, 1914.

Mathematical formulae for determining the absorption and the velocity of transmission of "long" earthquake waves are developed.

The geographical coordinates of, and times of origin at, the epicentra of eighty-eight earthquakes recorded during the period 1905-10 are tabulated. Another table includes the epicentral distances of these earthquakes from Jena, Göttingen, Hamburg, and Potsdam.

A. F. Rogers.

DIE FORTSCHRITTE IN DER DYNAMIK DER FESTEN ERDRINDE, 1905-08, by E. Tams. *Geographisches Jahrbuch,* 35, 1-80.

Thirty pages of this review are devoted to an account of the work done in seismology. There are over two hundred titles, arranged under the following headings: (1) Organization of seismological societies and stations; bibliographies and text-books; (2) Seismological apparatus; (3) Earthquakes waves; (4) Relation between earthquakes and other phenomena; (5) Sound phenomena; (6) Special notes; (7) Microseismic movements; (8) Applied seismology; (9) Cause and geographical distribution of earthquakes; (10) Description of individual earthquakes; (11) Earthquake catalogues. Brief abstracts of many of the articles are given.

This annotated bibliography is valuable, for the period covered (1905-08) is an important one in the development of seismology.

A. F. ROGERS.

The following abstract of a paper by Otto Klotz, read before Section B (Physics) of the American Association for the Advancement of Science during the convocation week beginning December 29, 1913, appeared in *Science,* June 12, 1914, p. 882.

"The most important seismological apparatus, the data obtained by them, and the conclusions logically deduced from these data, were all discussed at some length. A full and interesting account, together with many illustrations, was given of a recent installation of seismological apparatus that registers in magnified form even those small vibrations of the earth's crust caused by the passages of ocean waves."

UEBER DIE GEOGRAPHISCHE VERTEILUNG DER EPIZENTRALGEBIETE VON WELTBEBEN UND IHRE BEZIEHUNGEN ZUM BAU DER ERDRINDE, by Dr. E. Rudolph. *Compte Rendu du XIe Congres Géologique International.*

The author gives a brief critical review of the work of Montessus de Ballore and John Milne. According to the statistical work of the former, earthquakes occur in greatest numbers in two narrow zones, the Mediterranean and the circum-Pacific. These results must be modified to some extent, because only the perceptible quakes were considered, since a statistical investigation is chiefly limited to the land. Newer observations make it probable that there are on the bottom of the sea just as many and as active seismic regions as on the land.

It has been shown that a large number of the earthquakes felt in Japan had their origin in the sea east of Japan. It has likewise turned out to be true that for the whole circum-Pacific region the heaviest earthquakes come from the ocean, with their epicenters near the coast.

The author prepared a map based on records of the years 1903-1909, showing the principal macroseisms, with their epicenters determined as accurately as possible, and also the principal structural lines of the earth, to indicate the relationship between structural lines and disturbances. The map shows the bunching of epicenters of the Pacific zone in three places: in the Aleutian Islands, in the Bay of Yedo, and in the Philippines.

It is further shown on the map that in the Pacific, in the Indian, and in the Atlantic oceans, the lines of epicenters of macroseisms are connected with coasts of the Pacific type of structure.

The sharp contrast between the Atlantic and the Pacific regions may be due not merely to the different structures of the two, but even possibly to the different conditions in the deeper parts of the earth's crust.

By a comparative study of the occurrence of the major earthquakes in the three great regions, the author reaches the conclusion that they are intimately connected with the structural lines, and that the epicenters are somewhat constant. Those associated with the lines of the great dislocations or breaks that cut to unknown depths into the earth's crust be calls *fault-quakes.* Contrasted with these are the much more numerous microseisms, terrestrial and submarine, chiefly associated with folded regions. They are probably to be connected with the smaller faults that are constantly associated with folding in mountain-making, and hence are termed *fold-quakes.*

J. P. SMITH.

Seismological Reports Received

We beg to acknowledge receipt of the following reports from the seismological stations mentioned below. It will be noted that some sets are incomplete. We should be glad to have our colleagues fill them out if possible.

J. C. Branner, *Stanford University, California.*

St. Ignatius College Observatory. F. L. Odenbach, S.J., Director.—Seismological Bulletin, 1914; record sheets for August and September, 1911.

St. Louis University, Jesuit Seismological Service.—Record of the Earthquake Station, nos. 1-3, 1911; 1, 1912.

University of Santa Clara, Jesuit Seismological Service.—Nos. 28 (1910) to 124 (1913).

Harvard University, Seismographic Station Record.—Nos. 3-14 (1911); 15-31a (1912); 32-46 (1913); 1-7 (1914).

Dominion Astronomical Observatory, Earthquake Station, Ottawa, Canada.—Nos. 1-25 (1913); 1-3, 5-7, (1914).

Instituto Geologico Nacional, Tacubaya, Mexico.—Records for August 9, September 29, and November 19, 1912.

Museo Nacional, San Jose, Costa Rica.—Jan. 1, 1911.

Boletin del Servico Sismologico de Chile, Nos. 1, 2, 3. Santiago, 1912.

Observatorio Nacional do Rio de Janeiro, Brazil.—December 6, 1911; December 7, 8, 1912.

Seismological Bulletin of the Observatory, Manila, P. I.—Nos. 20-44 (1913); 1-15 (1914).

Catalogue of Philippine earthquakes, 1913. Reprint from the Weather Bureau for December 1913.

Stonyhurst College Observatory. Rev. W. Sidgreaves, S.J., Director. Stonyhurst, England.—November 1911 to March 1914.

Publications du Bureau Central de l'Association Internationale de Sismologie. Catalogue Regional des Tremblements de Terre 1906, 1907, 1908. Strasbourg.

Jena, Monatsberichte der Hauptstation f. Erdbebenforschung.—January 1910 to October 1910; December 1910 to June 1912.

Nachrichten des Taunus-Observatoriums zu Frankfurt-a. M.—Nos. 1-6 (1913); 1, 2 (1914).

Mitteilungen der Hauptstation f. Erdbebenforschung, Hamburg.—19-25 (1910); 39-45 (1911); 1-37 (1912); 1-43 (1913).

Bollettino della Societa Sismologica Italiana, vol. I, 1895, to date.

Bullettino Sismologico del R. Osservatorio di Catania ed Etneo.—August to December, 1910; January to April, June and July, 1911.

Estacion Sismologica de Cartuja, Granada (Spain).—Nos. 1 (January 1911) to 3 (Marzo 1914).

Zi-ka-wei, China. Bulletin Sismique de l'Observatoire.—Nos. 1 (1912) to 4 bis (1914).

Observatoire de Ksara. Bul. sismique.—Nos. 1-20 (1913).

MINUTES OF THE MEETING OF THE BOARD OF DIRECTORS OF THE SEISMOLOGICAL SOCIETY OF AMERICA, APRIL 22, 1914

The meeting was called to order by Vice-President Lawson at 2:30 p.m., in room 752, Phelan Building, San Francisco, Cal. Directors Branner, Lawson and Townley were present, and Directors von Geldern, Louderback and Tolman were represented by proxies.

The minutes of the meeting of the Board of Directors held on December 15, 1913, were read and approved.

The report of the Board of Election was read and accepted, and the following named members were declared elected directors of the Society for the ensuing year.

H. F. Bain,
J. C. Branner,
H. W. Fairbanks,
A. C. Lawson,
G. D. Louderback,
A. G. McAdie,
C. F. Marvin,
H. F. Reid,
C. F. Tolman, Jr.,
S. D. Townley,
O. von Geldern,
J. B. Woodworth.

(The committee's report is attached to these minutes.)

The election of officers for the ensuing year was the next order of business, and the following were duly nominated and elected:

G. D. Louderback	President
J. B. Woodworth	First Vice-President
C. F. Tolman, Jr.	Second Vice-President
H. F. Bain	Third Vice-President
S. D. Townley	Secretary-Treasurer

The report of the Secretary-Treasurer was read and accepted.

Nine new members, whose names are subjoined hereto, were recommended by Dr. Branner and the Secretary, and duly elected to membership in the Society. The Library of the University of Texas was placed on the list of subscribers.

By motions duly seconded and carried the Treasurer was instructed to transfer $25.00 from the Sayles Fund to the Life Membership Fund in order to represent the life membership of Mr. Sayles; the auditing committee was instructed to audit the accounts of the Treasurer; the salary of the Secretary-Treasurer was continued for one year at the rate of $20.00 per month.

The Secretary reported the resignations of several members, and also mentioned several members whose dues had not been paid since 1908. No action was taken. The meeting of the Society to be held in Seattle was discussed.

Adjourned at 3:10.

S. D. Townley, *Secretary.*

REPORT OF THE BOARD OF ELECTION

The annual election of directors of the Seismological Society of America was held in Room 752, Phelan Building, San Francisco, Cal., on April 4, 1914.

The report of the Board of Election is as follows:

President and Members of the Seismological Society:

We, the undersigned judges of election, certify that 147 ballots were cast at the annual election, held in San Francisco on this date, with the following result:

H. F. Bain	103
J. C. Branner	141
E. F. Davis	55
H. W. Fairbanks	94
A. C. Lawson	131
A. Lietz	49
G. D. Louderback	132
A. G. McAdie	116
C. F. Marvin	114
J. K. Moffitt	52
F. L. Odenbach	30
H. F. Reid	125
J. A. Taff	52
C. F. Tolman, Jr.	82
S. D. Townley	130
O. von Geldern	94
L. Wagoner	35
J. B. Woodworth	119
R. W. Sayles	1

The following named, being the twelve receiving the highest number of votes, are declared elected directors of the Society for the year 1914-15: H. F. Bain, J. C. Branner, H. W. Fairbanks, A. C. Lawson, G. D. Louderback, A. G. McAdie, C. F. Marvin, H. F. Reid, C. F. Tolman, Jr., S. D. Townley, O. von Geldern, J. B. Woodworth.

D. S. Richardson,
E. F. Davis.

April 4, 1914.

MEMBERS ELECTED APRIL 22, 1914

William R. Cullen, S. J.: Worcester, Mass.
J. W. Green: Washington, D. C.
J. C. Jones: Reno, Nev.
Warren Olney, Jr.: San Francisco, Cal.
M. M. O'Shaughnessy: San Francisco, Cal.
R. Speight: Christchurch, N. Z.
Francis A. Tondorf, S. J.: Washington, D. C.
Charles E. Weaver: Seattle, Wash.
James S. Wroth: Chuquicamata, Chile.

NEW SUBSCRIBER

Library of the University of Texas: Austin, Texas.

REPORT OF SECRETARY-TREASURER

From April 5, 1913 to April 4, 1914

During the period of this report the membership of the Society has remained practically stationary, the number now being 427. One member has been lost thru death, Professor C. G. Rockwood, of Princeton, N. J., who died on July 2, 1913, at the age of seventy years. Mr. Ricardo M. Arango, of Panama, a notice of whose death was printed in the last number of the BULLETIN, was one of the original members of the Society. Mr. Arango resigned in 1912 when failing health made it necessary for him to give up active work.

Volume 3 of the BULLETIN was issued during 1913. This volume contains 226 pages and 5 plates.

The financial report is as follows:

GENERAL FUND

Dr.

To balance, April 5, 1913	$ 16.74
Dues and subscriptions	741.00
Reprints	9.40
Sale of publications	3.50
Transfer from Sayles Fund, interest	272.43
Transfer from Sayles Fund, principal	100.00
Transfer from Life Membership Fund, interest	14.95
Total	$1,158.02

Cr.

By Stanford University Press, printing Volume 3	$ 710.75
Stanford University Press, miscellaneous printing	30.25
Commercial Art Co., illustrations	39.72
Second-class postage on BULLETINS	7.41
Foreign postage on BULLETINS	10.73
Miscellaneous postage	8.60
Stamped envelopes	42.48
Dues, Pacific Association of Scientific Societies	5.00
Rent of safety deposit box	2.00
Salary of Secretary-Treasurer	240.00
Balance, April 4, 1914	61.08
Total	$1,158.02

LIFE MEMBERSHIP FUND

Dr.	
To balance, April 5, 1913	$350.00
Two life memberships	50.00
Interest from Berkeley Bank of Savings and Trust Co.	14.95
Total	$414.95
Cr.	
By interest, transferred to General Fund	$ 14.95
Balance, April 4, 1914	$400.00
Total	$414.95

SAYLES FUND

Dr.	
To balance, April 5, 1913	$4,800.00
Interest from Mutual Building and Loan Association of San Jose and College Park	60.00
Interest from Palo Alto Mutual Building and Loan Association	120.00
Interest from Truckee Lumber Co.	60.00
Interest from Bank of Palo Alto, Savings Department	32.43
Total	$5,072.43
Cr.	
By transfer to General Fund, interest	$ 272.43
Transfer to General Fund, from Bank of Palo Alto	100.00
Balance, April 4, 1914	4,700.00
Total	$5,072.43

S. D. TOWNLEY, *Secretary-Treasurer.*

MINUTES OF THE MEETING OF THE SEISMOLOGICAL SOCIETY OF AMERICA, MAY 22, 1914

The meeting was called to order by President Louderback at 3 p.m., in Room 3, Science Hall, University of Washington, Seattle.

The minutes of the meeting held April 10, 1913 were read and approved.

The President appointed Professor A. C. Lawson to represent the Society at the meeting of the Council of the Pacific Association of Scientific Societies to be held on May 23d.

The following program was presented:

The California Earthquake of 1906, with special reference to the Earth Movements (illustrated with lantern slides), by S. D. Townley.

The Lisbon Earthquake of 1755, by H. F. Reid (read by Professor Lawson).

Arequipa Earthquakes Registered during the year 1913, by Leon Campbell (read by the Secretary).

The meeting adjourned at 4:30.

S. D. TOWNLEY, *Secretary.*

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

I. **Microseismic shock**: recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. **Extremely feeble shock**: recorded by several seismographs of different kinds; felt by a small number of persons at rest. some startled persons leave their dwellings.

III. **Very feeble shock**: felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. **Feeble shock**: felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.

V. **Shock of moderate intensity**: felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.

VI. **Fairly strong shock**: general awakening of those asleep, general ringing of house bells; oscillation of chandeliers; stop-

VII. **Strong shock**: overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. **Very strong shock**: fall of chimneys, cracks in walls of buildings.

IX. **Extremely strong shock**: partial or total destruction of some buildings.

X. **Shock of extreme intensity**: great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

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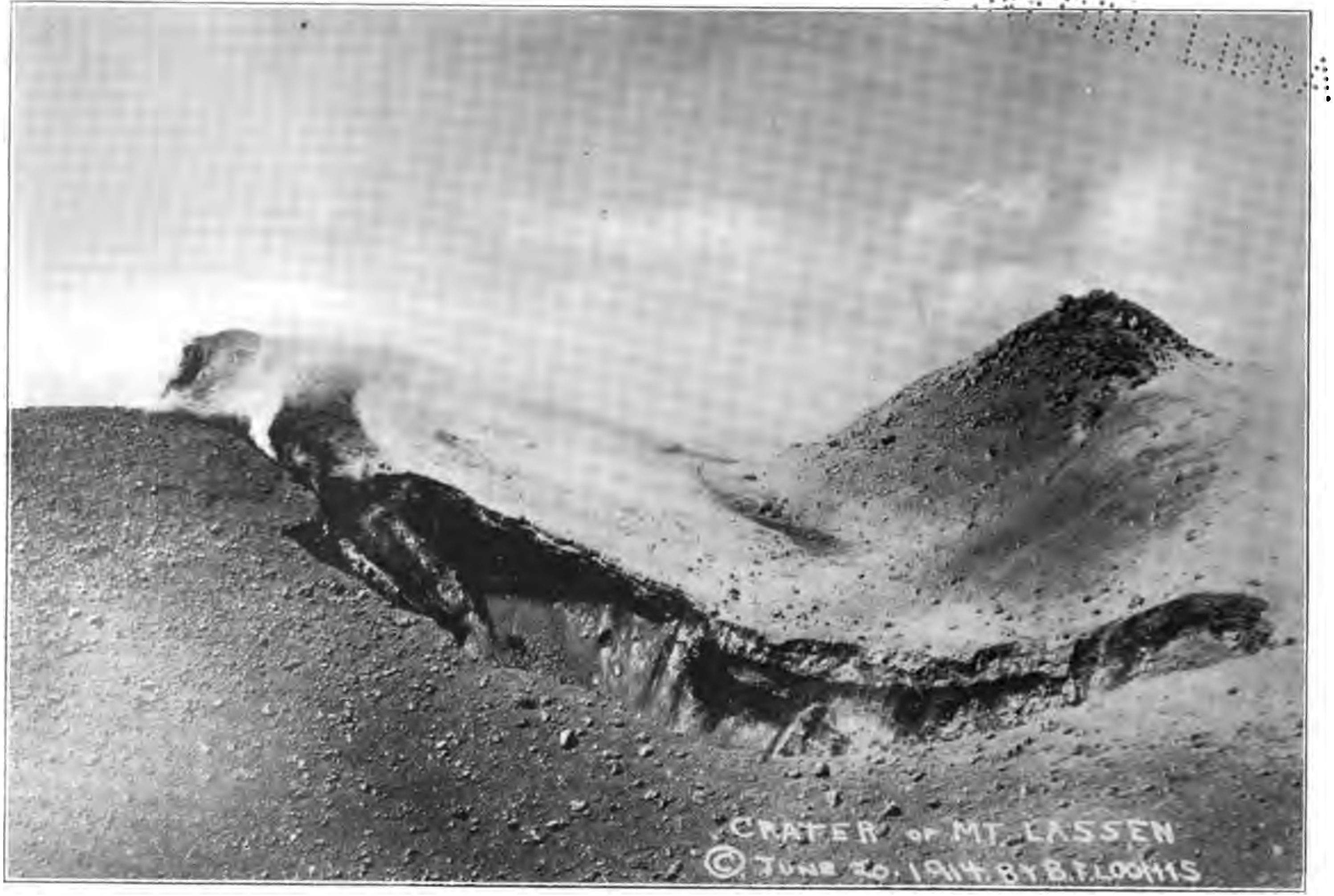

Crater of Lassen Peak, June 20, 1914.

The Bulletin of the
Seismological Society of America

VOL. IV SEPTEMBER, 1914 NO. 3

THE ERUPTIONS OF LASSEN PEAK, CALIFORNIA.[1]

By J. S. Diller.

The recent eruptions of Lassen Peak have been a great surprise not only to the residents of the district, but also to most of the geologists who are more or less familiar with the decadent volcanic energy of the Cascade Range. It is generally considered the "land of the burnt out fires," and so it is; but although the fires may be out, there is much evidence of remaining heat in some places upon the summits of the great volcanoes, as in the case of Shasta and Rainier and in others about the base of the mountain, where basaltic eruptions are likely to follow around an andesite cone.

Of all the great extinct volcanoes of the Cascade Range, Lassen Peak is the richest in solfataric action. Southeast of Lassen Peak there are Bumpass' Hell, Lake Tartarus, the Geyser, and the Devil's Kitchen, beside many other hot sulphurous springs, all of which are exhibits of volcanic energy, and a short distance to the northward is the Cinder Cone, a national monument which marks the scene of one of the largest volcanic eruptions in the United States.

The accompanying illustrations give a vivid impression of the character of the late eruptions of Lassen Peak. According to the forestry service at Mineral, there have been thirty-two eruptions up to August 23d. The eruption at 5:28 a.m. Saturday, July 18th, is said to have been "by far the most violent eruption to date," lasting practically the entire morning and ejecting the dust to a height of 11,000 feet. The outbreak August 21st is reported as "one of the largest," continuing an hour and forty minutes, the column rising to a height of 10,560 feet.

The five illustrations showing the mountain in action are numbers 1, 2, 3, 4, and 5, in a series of six views taken in close succession on the morning of June 14th during the ninth eruption, which lasted about half an hour and is said to have sent the dust up to 2,500 feet.

The crater increased in size with the number of eruptions. The view, reproduced in the frontispiece, was taken June 20th, after eleven eruptions. On July 23rd, after twenty-four eruptions, the crater was somewhat more than six hundred and fifty feet long,[2] one hundred to two hundred feet wide and about one hundred and fifty feet deep.

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[1] Published by permission of the director of the U. S. Geological Survey.

The material ejected ranges in size all the way from fragments four feet in diameter to fine dust. As the amount ejected at each eruption is small, only about ten feet in thickness of the rim is made of ejected material. Beneath it is a layer of snow that covered the place when the first outburst occurred May 30th.

The inner slopes are very steep and cave in frequently. A few large stones have been thrown more than a fourth of a mile from the crater. Most of the dust falls within a radius of a mile but some has been carried by the wind as much as fifteen miles to the southward, and the sulphurous fumes are said to have been recognized at about the same distance. A quarter of a mile from the crater, to the southwest, the sand and dust layer on the snow, July 23rd, was three inches thick, and being wet, looked, from a distance, black and peculiar on the white snow. When dry this dust is very light and easily carried by frequent whirlwinds into the air to make the mountain look as if it were smoking. Forest rangers who were in the neighborhood of the summit during eruptions heard the rushing steam and the falling rocks, but report no rumbling or subterranean noises, earth shocks,[3] electrical phenomena, or great heat beyond that of the escaping steam.

Considerable volumes of water were ejected, probably wholly in the form of steam. The water condensed as rain, but there was not enough of it to produce any marked effect by eroding the surface, and the phenomenon is in no proper sense a geyser.

Within the crater the yellowish surfaces suggest that sulphur is being deposited by the rising vapors as in the solfataras. No definite molten products have been found as a result of the recent eruptions of Lassen Peak. The dust sent to Washington was examined microscopically by H. G. Ferguson, who came to the conclusion that the dust afforded no evidence of recent fusion.

I examined the crater the second time July 23rd and found it to be larger and emitting a greater quantity of steam more generally distributed over the crater bottom than on June 20th when the first examination was made.

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[2] Paced by W. H. Storms, June 21st, *Mining and Scientific Press*, July 25, 1914.

[3] William H. Storms reports a moderately heavy shock in the latter part of May. *Mining and Scientific Press*, July 1914, p. 143.

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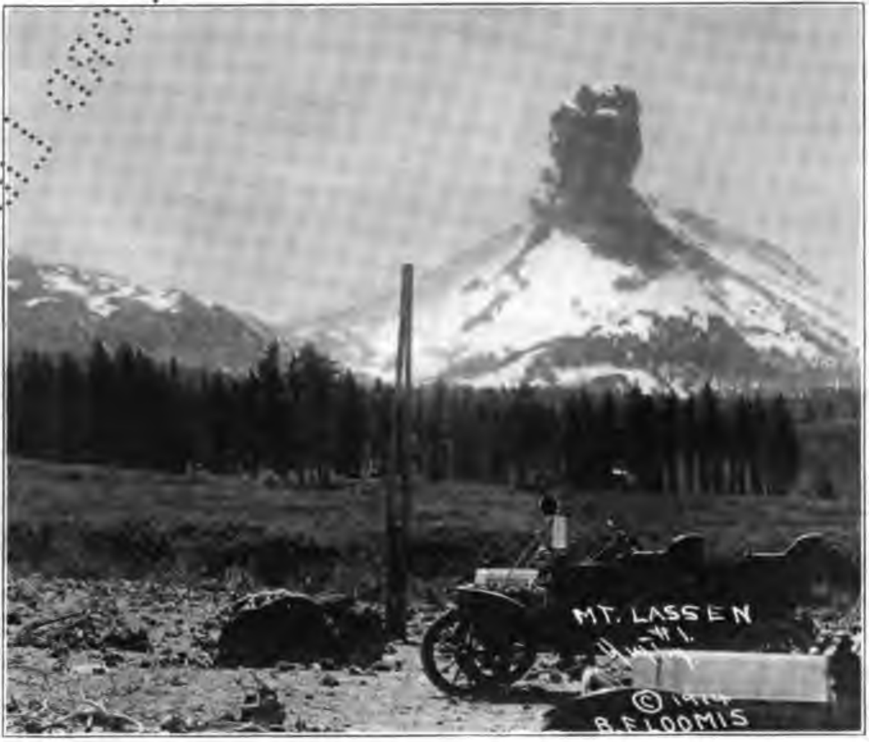
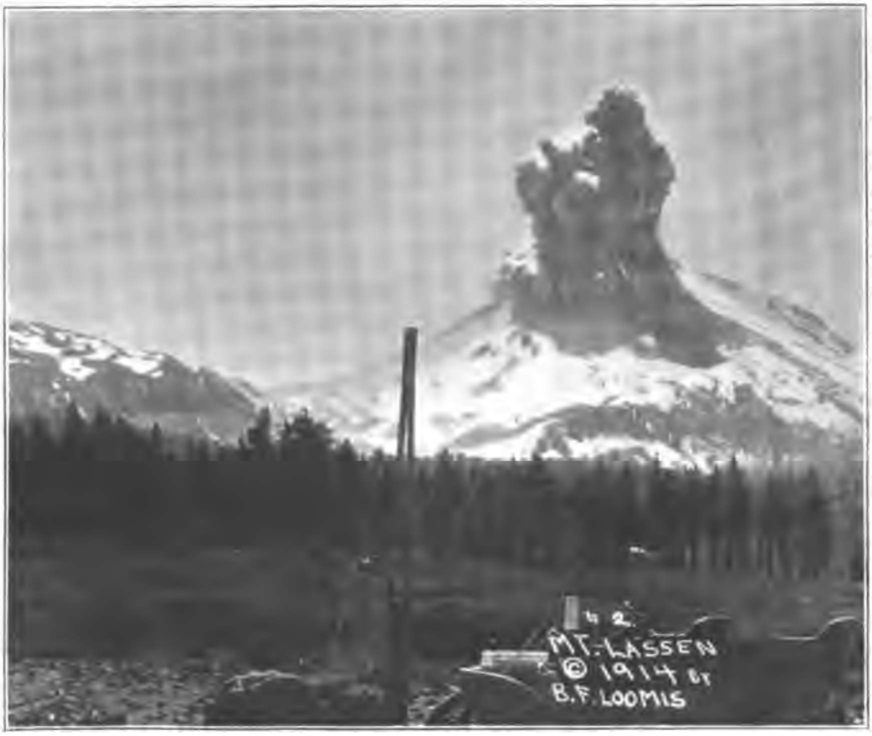
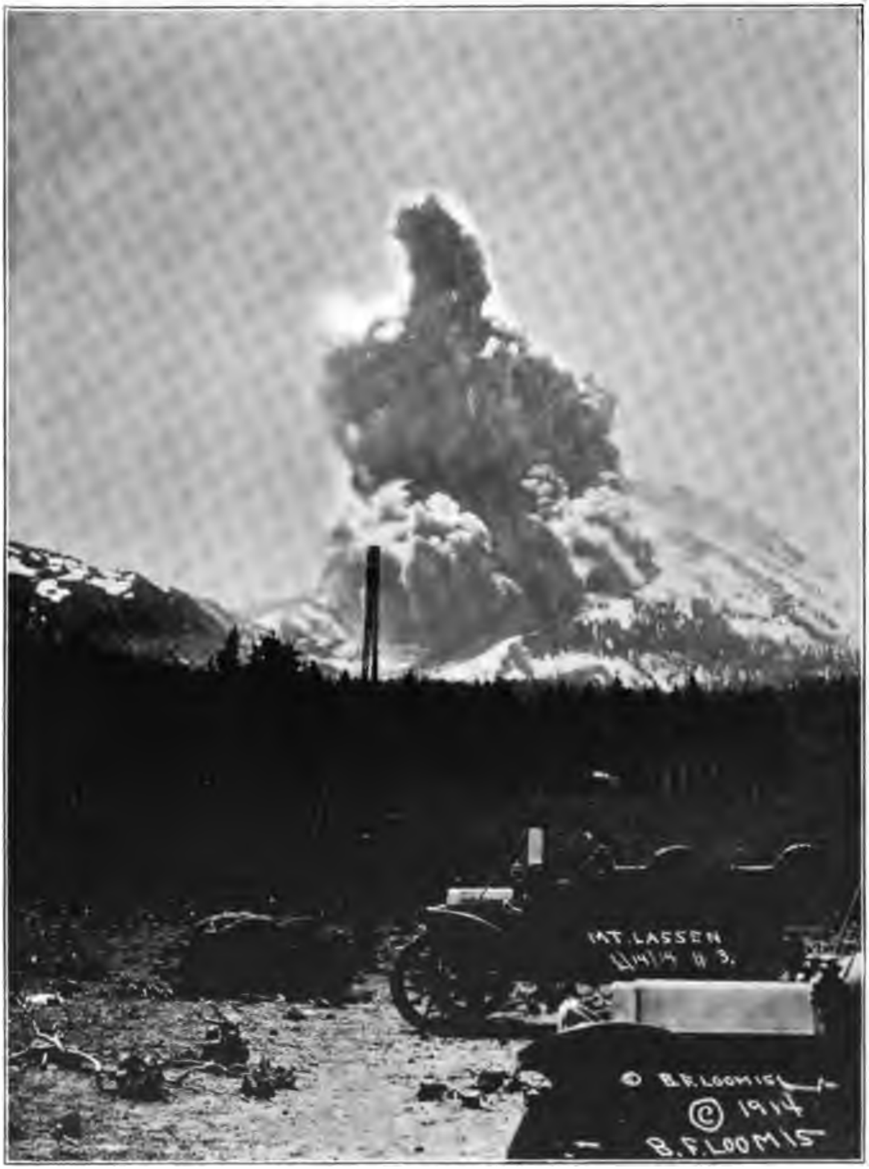


Eruption of Lassen Peak, June 14, 1914, at 9:45 a. m.



Eruption of Lassen Peak, June 14, 1914, at 9:50 a. m.



Eruption of Lassen Peak, June 14, 1914, at 9:55 a.m.

During the ten days ending July 18th nine eruptions, including the two largest, have been reported by the forest service; while in the ten days previous there were only six eruptions of moderate size. During June there were twelve eruptions, and in July up to the 19th there were eleven eruptions. Although the records show increased intensity of volcanic action there seems to be as yet no impending danger of a sudden disastrous eruption. The activity appears to be limited to a comparatively shallow depth at the summit of the mountain.

Nearly all the hot springs and solfataras about Lassen Peak have been visited recently and the common opinion found true that there is no evidence of increased intensity in the solfataras since the eruptions from the summit of Lassen Peak began.

The eruptions will probably end in establishing a solfatara on the summit of Lassen Peak, but it should be closely watched for earth tremors and evidences of deeper seated action, and visitors should approach it with caution.

There are excellent views of Lassen Peak at a distance of about fifty miles, from the Southern Pacific trains between Redding and Cottonwood, especially at Panorama Point, a few miles south of Anderson.

The forest service at Mineral, W. J. Rushing, forest supervisor in charge, has an outlook station on Broke Off Mountain, in full view of Lassen Peak, only a few miles away to the northward. Mr. Rushing is on Broke Off Mountain, a part of Lassen's oldest crater rim, continuously, and has an excellent opportunity to make a complete record of Lassen's activity, a service of great importance.

Lassen Peak may be reached from Redding, on the Southern Pacific railway, thence by motor to Viola P. O. and Manzanita Lake, but the motor trip is long and the mountain climb from the northwest is hard.

A better way is from Red Bluff, on the Southern Pacific railway, thence by motor to Mineral Postoffice, thence horseback twelve miles to the foot of the mountain, and an easy climb of about an hour and a half to the summit from the southeast.

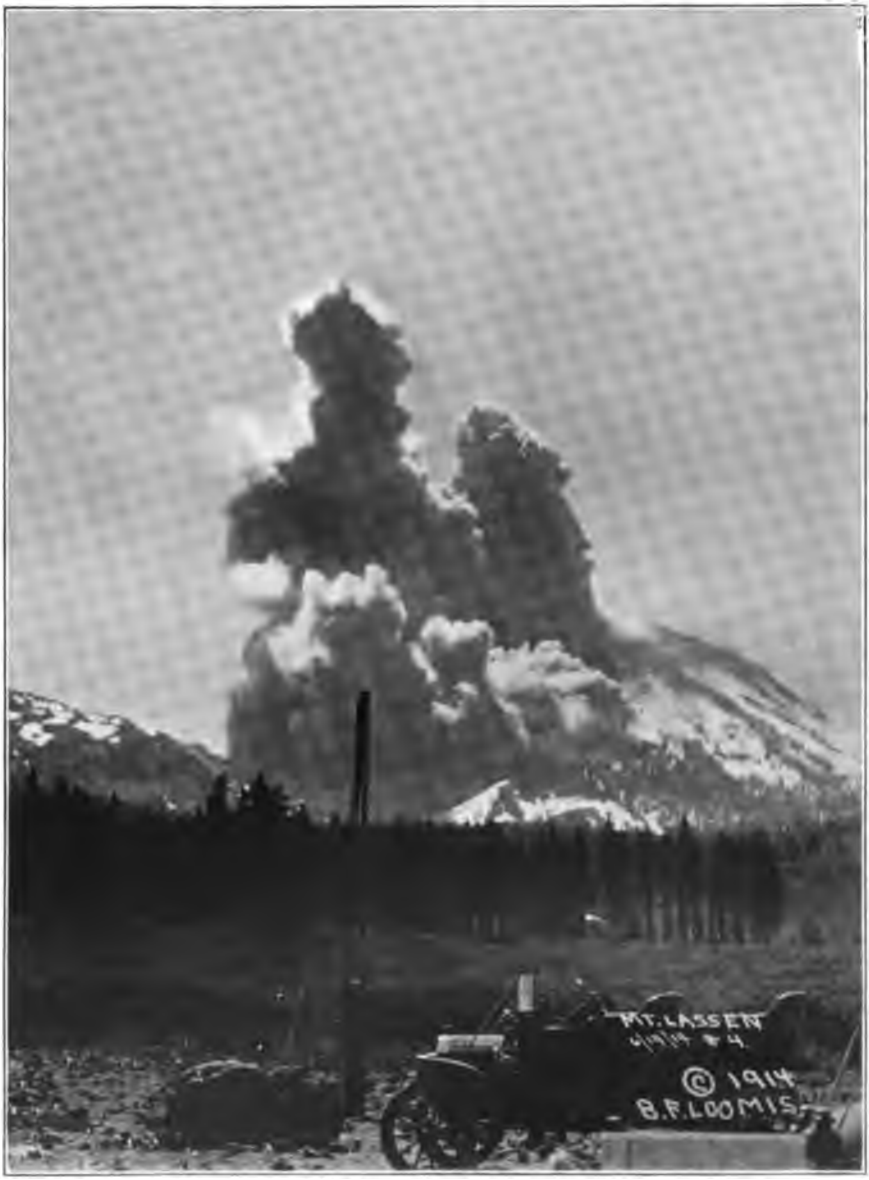
The best way is from Drakesbad on the southeast, only seven miles from the mountain. Drakesbad, formerly Drake's Springs, is an attractive mountain resort in Hot Spring Valley, from which not only Lassen Peak but also Cinder Cone and other interesting volcanic phenomena may be easily visited.

Drakesbad is a thirty-mile motor ride from Westwood, the fine hoteled terminus of the Southern Pacific branch line from Fernley.

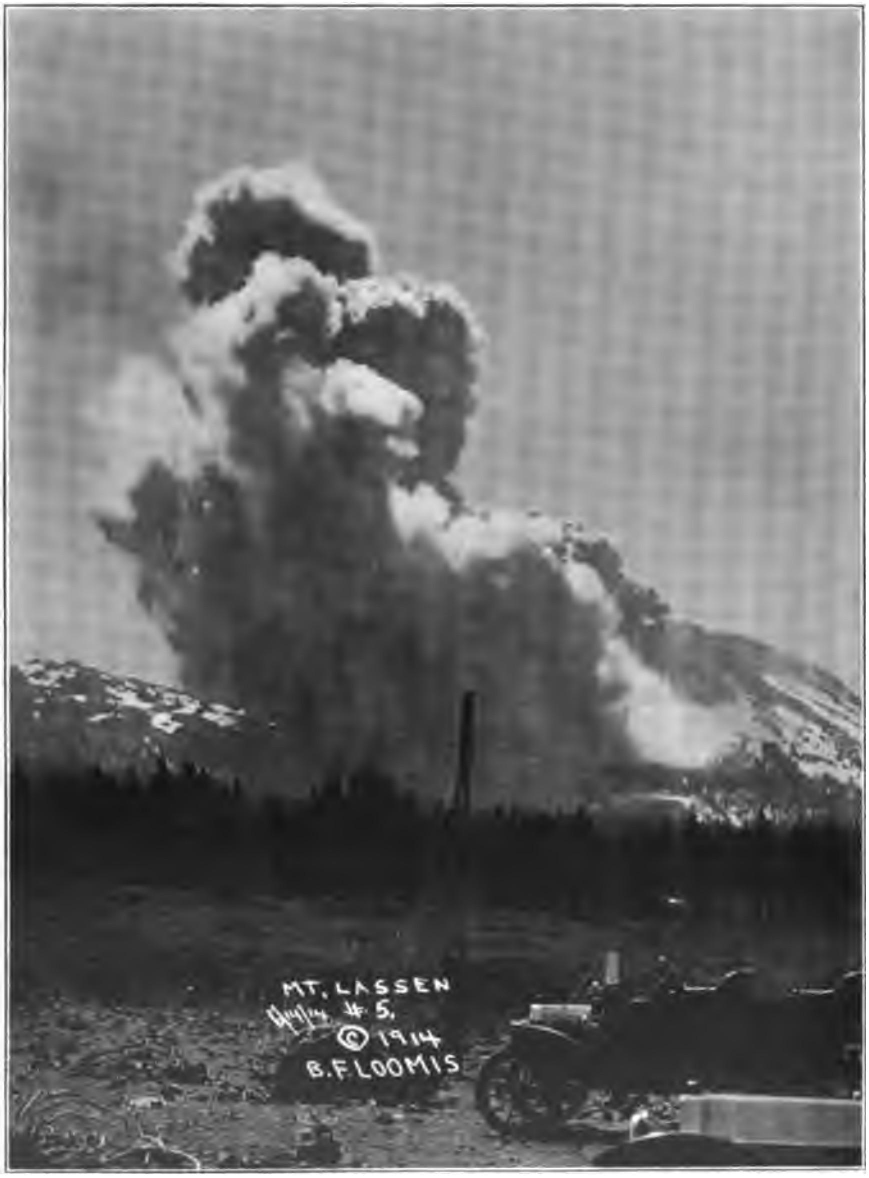
ERUPTIONS OF LASSEN PEAK

No. of Eruption	Date 1914	Time P. S. T.	Character of Eruption	Duration	Size of Crater in Feet
1	May 30	5:00 p.m.	Heavy.	10 min.	25x40
2	June 1	8:00 a.m.	Heavier.	15 min.	275x60 60 deep
3	June 2	9:30 a.m.	Very heavy.	30 min.	
4	June 8	4:30 p.m.	Heavier.	40 min.	
5	June 9	10:30 a.m.	Heavy. Steam darker.	30 min.	
6	June 12	3:45 p.m.	Heavy. Steam very dark.	50 min.	400x100
7	June 13	6:00 a.m.	Ashes fell at Mineral. Heavy.	30 min.	
8	June 14	6:00 a.m.	Unconfirmed. Reported by Red Bluff.	?	
9	June 14	9:43 a.m.	Altitude smoke, 2500 feet. Heaviest yet.	30 min.	
10	June 14	6:45 p.m.	Medium.	15 min.	450x125
11	June 19	8:15 p.m.	Altitude smoke, 2000 feet. Medium.	15 min.	600x150
12	June 29	3:00 a.m.	New snow covered by layer of ash.	?	
13	June 30	11:06 a.m.	Heavy. Series of slight eruptions followed first. Altitude, 2800 feet.	40 min.	
14	July 1	5:30 a.m.	Heaviest yet. Altitude, 5900 feet.	50 min.	
15	July 2	6:50 a.m.	Very heavy.	30 min.	
16	July 6	3:30 a.m.	Reported by Red Bluff. Heavy. Steam and smoke from entire length of the crater.	30 min.	
17	July 13	3:07 p.m.	Medium. Air calm. Thin column of steam rose to height of 1800 feet. Little ash visible. West end crater.	40 min.	
18	July 15	6:05 a.m.	Very heavy. Of long duration.	4 hours.	
19	July 15	12:05 p.m.	Greatest disturbance thus far. Exceeded previous eruptions in intensity and duration. Great quantities dust thrown out.	Entire afternoon.	
20	July 16	12:30 a.m.	Very heavy. Volcanic dust fell at Mineral.	Intermittently through early hours.	
21	July 16	4:30 a.m.	Heavy eruption.	Several hours.	
22	July 17	6:00 a.m.	Heavy eruption. Volcanic ash fell at Mineral.	Several hours.	
23	July 17	11:47 a.m.	Heavy eruption.	Several hours.	
24	July 18	5:28 a.m.	By far most violent eruption to date. Ash, steam, etc., rose to height of 11,000 feet.	Practically entire morning.	
25	Aug. 10	5:30 p.m.	Medium. Small quantity ash thrown out.	Continued after dark.	
26	Aug. 19	7:24 a.m.	Very heavy. Huge clouds ash thrown out. Height, 10,500 feet.	4 hrs. 30 min.	
27	Aug. 21	11:10 a.m.	One of the largest eruptions to date. Entire crater active. Height, 10,560 feet.	1 hr. 40 min.	
28	Aug. 22	8:40 a.m.	Heavy. Ash column shot up obliquely, instead of vertically as in all former eruptions. Altitude, 7590 feet.		
29	Aug. 22	12:40 p.m.	Heavy. Entire crater active. Height, 5940 feet.	1 hr. 20 min.	
30	Aug. 22	4:35 p.m.	Medium. Height, 6000 feet.	55 min.	
31	Aug. 23	6:33 a.m.	Medium. Height, 5610 feet.	1 hr. 53 min.	
32	Aug. 23	7:43 p.m.	Larger than morning disturbance. Height, 5940 feet.	Continued after dark.	

Of the thirty-two eruptions listed above there were sixteen with an interval between them of less than a day, six with an interval of between one and two days, two between two and three days, two between three and four days, and five with intervals of from five to twenty-three days. It is noteworthy that the longest interval, twenty-three days, followed the most violent eruption, and was succeeded by one of low intensity.



Eruption of Lassen Peak, June 14, 1914, at 10:00 a. m.



Eruption of Lassen Peak, June 14, 1914, at 10:10 a. m.

Nevada, to Susanville. There is a through sleeper from San Francisco to Susanville on train No. 6.

The Western Pacific railway affords an easy approach by way of Keddie and thence by motor to Westwood, or from Doyle to Susanville.

The list of eruptions and data concerning them given on the preceding page were kindly furnished by Mr. Rushing.

SEISMIC ACTIVITY IN THE ATLANTIC COASTAL PLAIN NEAR CHARLESTON, SOUTH CAROLINA.[1]

By Stephen Taber

INTRODUCTION

It is not generally known that earthquakes are still of frequent occurrence in the epicentral region of the historic Charleston earthquake of August 31, 1886, and yet during the past fifteen years they have been recorded at the average rate of nearly one shock every two months. Eight earthquakes were recorded during 1912, and the shock occurring on June 12th of that year was of greater severity than any felt in the district since the disturbances of 1886-1887. The discovery of these facts prompted the writer to begin a detailed investigation of the cause of these earthquakes and of the various factors which may produce fluctuations in the seismic activity of the region. The present paper was prepared in order to place on record such facts as have been established and the conclusions that may be drawn from them.

LOCATION

The area within which the earthquakes occur is located near the southeastern edge of the Atlantic Coastal Plain in South Carolina between Charleston and Summerville, and at a distance of about twenty miles from the ocean. The census of 1910 gave Charleston a population of 58,833 and Summerville 2,355, but the country lying between these towns is very sparsely inhabited, the residents being almost entirely negroes. This has made it impossible to obtain detailed information concerning the shocks in the immediate vicinity of their origin, and therefore nearly all of the data on which the latter part of this paper is based have been obtained from Charleston and Summerville.

TOPOGRAPHY

The topography of the area is flat and low, the highest elevations probably nowhere exceeding sixty or seventy feet above mean sea level; much of the country is swampy, even at a distance from the coast; and almost the only relief is found in the occasional gentle ridges or hummocks a few feet in height which are believed to indicate the location of old beach lines. The district is drained by the Cooper, Ashley and Stono rivers with their tributaries, and near the coast there are numerous so-called rivers and creeks which are really brackish tidal channels connecting the different rivers and inlets. The larger streams are all navigable for vessels of medium draft. The numerous connecting waterways dissect the land into a group of islands that extend inland a distance of nearly fifteen miles, and some of the larger islands have an area of over seventy-five square miles. The margins of these islands are commonly higher than their interiors, indicating that the land has been built up, in part at least, of fluvial and tidal deposits. Extensive salt-water marshes are found along the tidal channels and farther inland there are numerous fresh-water swamps, which owe their origin to the position of the water-table, for springs are relatively rare. These fresh-water swamps are much affected by seasonal changes and the amount of rainfall.

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[1] This paper was read in part before the LeConte Scientific Society at the University of South Carolina, February 6, 1914.

GEOLOGY

In South Carolina the Coastal Plain attains a width of nearly 150 miles. The average elevation of its inner edge, where it overlaps the old pre-Cambrian crystalline rocks of the Piedmont, is about 500 feet above sea level. The slope of the surface from the inner edge toward the coast is at first rather steep, so that within thirty miles the elevation decreases to less than 200 feet, but from this line to the sea the slope is very gentle. The surface of the crystalline rocks, dipping beneath the overlapping sands and clays of the Potomac formation, extends for an unknown distance southeastward, having been reached in deep-well borings at several points in the Coastal Plain. At Wilmington, N. C., a well started only a few feet above tide level entered the granite at a depth of 1,109 feet. At Orangeburg, seventy-five miles northwest of Charleston, a well was drilled to a depth of 1,160 feet without reaching the crystalline basement, which is, however, probably not very far below. A well at Charleston, 2,050 feet deep, failed to reach the crystalline rocks and probably stopped in the upper layers of the Potomac.[2] It is, of course, impossible to predict at what depth the basement could be reached at Charleston, but probably it would be less than 3,000 feet and might be not more than 2,500 feet below sea level.

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[2] The descriptions of the water-bearing formations of the Coastal Plain given in this paper were largely abstracted from "Underground Waters of South Carolina," by Dr. L. C. Glenn. Water-Supply and Irrigation Paper, U. S. Geological Survey No. 114, 1905, pp. 146-147.

The Potomac formation, lying directly upon the old crystalline rocks, outcrops along the inner margin of the Coastal Plain in a belt that is five to ten miles wide, and, where exposed, consists of 400 or 500 feet of sands and clays. It is a water-bearing formation and was probably reached by the deep well at Charleston. Overlying the Potomac there are beds of marine Cretaceous, consisting of marls, clays and sands; and where this formation was pierced by the Charleston wells it extended from a depth of about 600 feet below the surface to about 1,900 feet.

The Eocene strata, near Charleston, occupy a basin-like depression in the Cretaceous and have a thickness of about 500 feet. At the base a bed of silicified clay is found, overlain by a more or less porous silicified mass of shells and casts which is usually water-bearing. The overlying strata consist chiefly of marls and extend in places to the surface, but are usually covered by a variable thickness of Pleistocene sands and clays.

Within the area in which the earthquakes occur much of the surface soil is underlain by sands saturated with water, and this layer is believed to have furnished the material of which the numerous sand craterlets were built up at the time of the earthquake in 1886. At Ten-mile Hill this bed of quicksand lies about twelve feet below the surface and has prevented the sinking of artesian wells.

CAUSE OF THE EARTHQUAKES

After the earthquake of August 31, 1886, Major Dutton, with the aid of several assistants, collected a large amount of data bearing on the disturbance and made a very careful and detailed investigation, but in the preface to his monograph,[8] published in 1889, he states that, "after the most careful and prolonged study of the data at hand, nothing has been disclosed which seems to bring us any nearer to the precise nature of the forces which generated the disturbance. Severe labor has been expended for many months in the endeavor to extract from them some indications respecting this question, but in vain. This problem remains where it was before. Having nothing to contribute towards its solution, I have carefully refrained from all discussion of speculations regarding the causes of earthquakes."[4] At the time this was written the old centrum theory of Mallet still retained vitality and strongly influenced the conclusions reached by Dutton and his co-workers, although their writings furnish evidence of the difficulties they encountered in reaching conclusions that would conform with this theory and at the same time with their observations.

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[8] Dutton, C. E. "The Charleston Earthquake of August 31, 1886." Ninth Annual Report U. S. Geological Survey, 1889, pp. 203-528.

During the last quarter of a century great advances have been made in the science of seismology, and today, in view of all the evidence that has accumulated, there can be no question but that the Charleston earthquake was due to the readjustment of rock strata under strain and should therefore be classed as tectonic in origin. Indeed, this was the final decision of Major Dutton himself, for in writing of "dislocation or tectonic quakes" in 1904, he states: "In the Charleston disaster, though no displacements other than those of the surface soil were indicated, the persistent after-shocks lasting through eight years or more are indications of subterranean dislocation, and not of deep-seated volcanic action."[5] It may be added that there is no evidence of igneous activity in the eastern part of North America since the Triassic period.

It is believed by the writer that most of the earthquakes felt in the South Carolina Coastal Plain during the last thirty years are probably to be attributed to readjustments taking place along a plane of faulting, located in the crystalline basement underlying the Coastal Plain sediments, not far from Woodstock, and extending in a general northeast-southwest direction. The facts on which this conclusion is based are given below.

Where the crystalline rocks are exposed in the Piedmont section of the State the prevailing strike of the schistosity and of the contacts between different rock formations is northeast-southwest; the belts of the Coastal Plain, representing different periods of sedimentation, extend in the same general direction, as does also the present coast line. These facts prove that the displacements or warpings which have resulted in the repeated elevation and depression of the Coastal Plain region, as well as the earlier and more important movements which folded, faulted and metamorphosed the rocks of the Piedmont, have for the most part taken place along axes running in a northeast and southwest direction.

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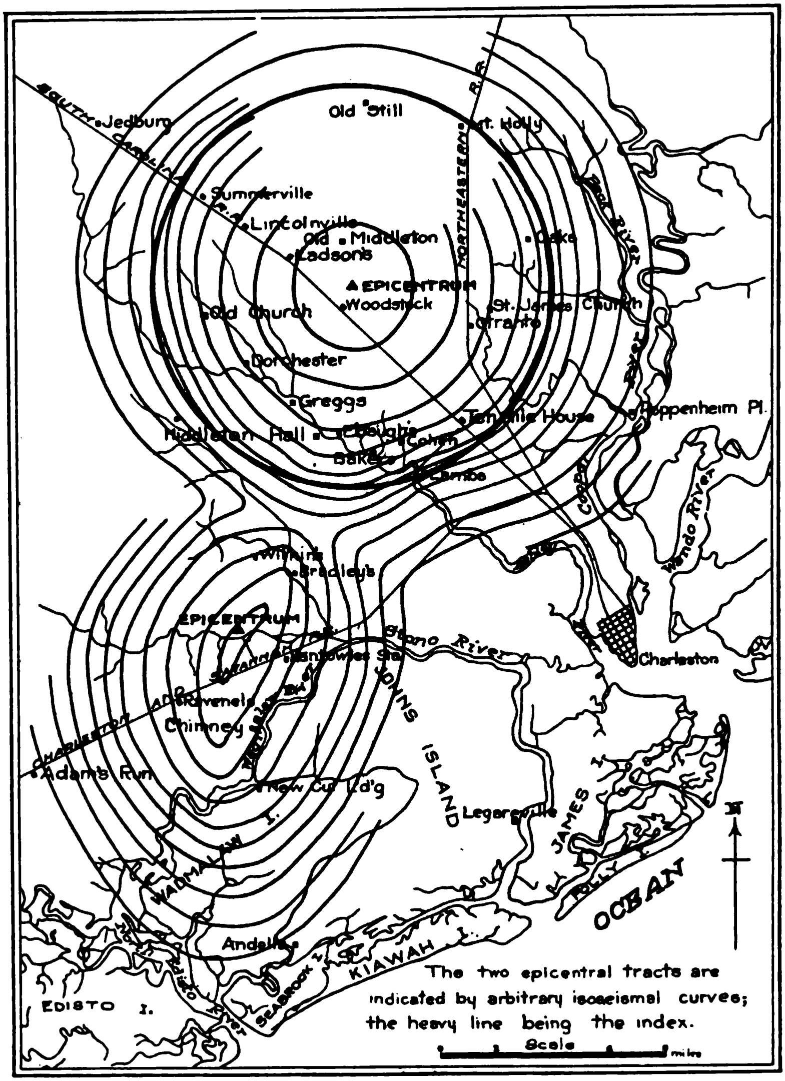
[4] Ibid., p. 211.

[5] Dutton, C. E. "Earthquakes in the Light of the New Seismology," 1904, p. 64.

More direct evidence of the orientation of the supposed fault near Woodstock is furnished by the distribution of intensities at the time of the catastrophe of August 31, 1886. On Plate XXVI of Dutton's monograph two epicenters are shown; the Woodstock epicenter, located near the Southern Railway, fourteen miles N. 30° W. of



The two epicentral tracts are indicated by arbitrary isoseismal curves; the heavy line being the index.

Fig. 1. Isoseismals. Charleston Earthquake 1886. Plate XXVI of Dutton's Monograph.

Charleston, and the Rantowles epicenter, fourteen miles due west of the city. The arbitrary isoseismal curves surrounding the latter are elongated in a northeast-southwest direction, but circular curves are drawn around the Woodstock epicenter. In making these curves circular Dutton frankly disagreed with Mr. Earle Sloan, who had spent over two months in the epicentral tract collecting the information used in drawing these very lines. Major Dutton states: "He [Mr. Sloan] is of the opinion that the isoseismal curves project considerably in a northeastern quarter."[6]

In an earlier paper read before the National Academy of Sciences in April 1887, Major Dutton announced that he believed "there were three distinct foci with as many epicentra, and that the third one was situated in the near neighborhood of the Ashley River and a little west of the line joining the other two," but this view was formally abandoned in the monograph.[7]

On Plate XXVII, entitled "Mr. Sloan's delineation of isoseismals in the epicentral tract," the curves are carried around both of Dutton's epicenters and are therefore markedly elongated in a northeast-southwest direction. The only irregularity is a protuberance extending toward Summerville, which may be merely an apparent increase in the intensity due to the underlying quicksand, for, as may be seen from Plate XXVIII, the sand craterlets were unusually abundant in this section.

Mr. Sloan stated his own conclusions as follows: "Many data of eloquent significance argue that the great earthquake shock . . . was a compound disturbance proceeding from a series of foci progressively explosive in a line of action northeast to southwest, each propagating its waves of force radiating in all directions."[8] Referring to the three railroads that radiate out from Charleston he says: "Considerations of these railroads, with their highly disturbed zones graduating to nil on either hand, warrants the assumption of an axial disturbance . . . An extensive series of observations indicate that the axis is composed of a series of foci, the major one of which . . . was located on the map with epicentrum fourteen miles N. 30° W. of Charleston."[9]

From the quotations given above it is clear that the intensity was greatest along an axis extending northeast and southwest, the maximum intensity occurring not far from Woodstock. If it were possible to locate accurately the epicenters[10] of each shock recorded in this region since 1886, most of them would probably fall along this axis, though not in the same place.

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[6] Ibid., p. 318.

[7] Ibid., p. 303.

[8] Sloan, Earle. "The Earthquake of August 31, 1886." *Year-Book of the City of Charleston,* 1886, p. 390.

[9] Ibid., p. 397.

The absence of all superficial indications of faulting at the time of the Charleston earthquake should not be surprising when it is remembered that the basement of crystalline rocks is buried beneath approximately one-half mile of unconsolidated sediments saturated with water. Under these conditions a displacement with considerable vertical throw might take place without producing noticeable evidence at the surface. Of course the displacement may have been entirely horizontal as in the California earthquake of 1906, but this method of faulting is probably rare as compared with displacements accompanied by some vertical throw.

Studies of the California earthquake have thrown much light on the mechanics of faulting. When great masses of the earth's crust are suddenly displaced, it is as a result of tremendous forces which in some way have been brought into action. In the case of the California displacement, gravity could not have been the direct cause, for the movement was horizontal, and it is highly improbable that gravity is ever the direct cause of vertical displacements along faults of considerable lateral extent, for it would necessitate the presence of underground cavities too extensive to be considered. The only forces of sufficient magnitude to accomplish these results are elastic forces brought into play through the gradual distortion of the rocks themselves. The great structural movements which have resulted in the elevation and depression of continents and the formation of mountain ranges are probably exceedingly slow, but they set up elastic stresses that may extend over wide areas. The stresses gradually accumulate until they become too great for the strength of the rocks, and then rupture occurs at the weakest place, usually along a fault-plane which has been the locus of previous adjustments. When the rupture occurs the displacement is an elastic rebound which relieves the condition of strain.[11]

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[10] The word "epicenter" as used by the writer does not refer to a point but to the area of high intensity immediately above the origin, whatever be its size and shape.

[11] Dr. H. F. Reid advocated the theory of elastic rebound as an explanation of the California Earthquake of 1906. Report of the California Earthquake Investigation Commission, 2, 1910.

If this hypothesis is true it follows that there is a limit to the amount of displacement which may occur along a given fault-plane at one time, and the limiting factors are: (1) the elastic limit and coefficient of elasticity of the rocks involved; (2) the stress necessary to cause rupture; and (3) the distance from the fault-plane to a region of no distortion. In other words, great faults having displacements of thousands of feet were formed only as a result of numerous small displacements, separated by periods of quiescence during which the elastic stresses were gradually accumulating. In some cases the friction of the rocks along the plane of faulting may prevent the complete relief of stress, and in others the momentum of the movement may carry the displaced masses beyond the position of no strain. The adjustment of these and other purely local stresses resulting from the larger movements explains many of the after-shocks that follow all great tectonic earthquakes.

FACTORS CONTROLLING TIME OF SHOCK

If stresses tending to cause vertical displacement along a fault are gradually accumulating, and, because of changing external conditions, there are variations in the relative pressure applied to the earth's surface on opposite sides of the fault, rupture would most likely occur at times when the effect of the varying surface pressure is to increase the gradually accumulating stress. Some of the more important agents which may temporarily cause differential loading of the surface on opposite sides of a fault-line are: (1) atmospheric pressure, (2) tides, (3) rainfall, (4) the height of the water-table as determined by rainfall, seepage, evaporation, etc., (5) floods, and (6) accumulations of snow and ice.

There have been many attempts to discover some relation between earthquake frequency and external periodic forces, such as the tidal influence of the moon and sun, but the most careful investigations have shown the effect if any to be very slight; and, if we accept the view held by most seismologists, that the majority of earthquakes are due to faulting, it becomes clear why this is necessarily true, for the stresses due to the varying attraction of the heavenly bodies are approximately the same over wide areas, producing almost no differential pressure on opposite sides of fault-lines. Similarly, surface loading by rainfall is commonly uniform over considerable areas; but, because of local topographic conditions, there may be marked differences in the amount of precipitation within small areas, and along sea coasts there may be important variations in the height of the water-table without corresponding variations in mean tide level.

Recently several investigators[12] have published data indicating an apparent increase of general seismic activity with increase in rainfall. In the opinion of the writer, it is improbable that the mere increase of pressure over a given area, due to rainfall or other cause, is sufficient to noticeably influence any tendency to displacement along faults. If the location of a given fault and the distribution of the rainfall are such that increased precipitation causes unequal loading and thus increases a gradually accumulating stress, then the tendency to displacement will be greater after heavy rains; but on the other hand, if the location of the fault and the distribution of the rainfall are such that increased precipitation lessens a gradually accumulating stress, then the tendency to displacement will be greater at times of drought.

In order to test the influence of various factors which may affect the seismic activity of the region near Charleston and Summerville, and if possible discover some evidence that would indicate the character of the movements occurring along the supposed fault, the writer has compiled a list of over 400 earthquake shocks (see table pp. 150 to 160), all of which are believed to have had their origin in this area. Only felt shocks are recorded, for there are no seismographs in this immediate section. Unfortunately, and in spite of every effort, the list is by no means complete, especially for the years 1886 to 1898; nevertheless, for most purposes it is fairly representative, and clearly indicates certain general conclusions.

RELATIVE SEISMICITY OF THE DISTRICT

Historical records show that the seismicity of this area was exceedingly low for at least two centuries prior to the period of activity beginning in 1886. No severe earthquakes had their origin in the area from the time of its settlement by white people in 1671 until the Charleston earthquake, and the most violent shocks recorded during this early period are those connected with the New Madrid disturbances in the Mississippi valley from 1811 to 1812. These shocks slightly damaged a few brick buildings at Columbia and elsewhere in the State, while in Charleston they were severe enough to set church bells ringing, stop clocks, and throw off one or two chimney tops.

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[12] Drake, N. F. "Destructive Earthquakes in China." *Bulletin Seismological Society of America*, **2**, 1912, 40-91 and 124-133.

Sayles, R. W. "Earthquakes and Rainfall." *Bulletin Seismological Society of America*, **3**, 1913, 51-56.

The earliest earthquake recorded in Charleston according to the list published by Mr. William A. Courtenay[13] was only a slight shock felt May 19, 1754; but the next one, occurring April 4, 1799, was more violent and was accompanied by a rumbling sound. These dates have not been verified, and the latter earthquake may be the same as one of those mentioned in James Kershaw's Diary, although the dates indicate that they are separate shocks. Kershaw states that at Camden, on April 11, 1799, at 3:20 a.m. there was a noise like thunder which shook the house and caused windows to rattle, the direction being south-southeast to northwest. He records a second shock at 2:55 p.m. of the same day.[14]

According to William L. King[15] there were no earthquakes felt in Charleston after the occurrences of 1811-1812 until February 7, 1843, when two slight shocks were felt a few minutes before 10 a.m. They are said to have been accompanied by a rumbling sound, and were noticed by many people in different sections of the city.

The next earthquake to be felt in Charleston occurred on December 19, 1857, and has been described by Professor Gibbes who gives the time as 9:3:40 a.m. mean time at Charleston, with a possible error of ten seconds. He states that there was no distinct shock or blow but a series of horizontal oscillations increasing gradually in distinctness, and subsiding somewhat more rapidly. The vibrations lasted six or eight seconds and were felt generally by adults and children on the ground floor. The earthquake was accompanied by a rumbling noise which was more noticeable in the quiet of the country. It was reported from several places near Charleston, and was perceived in Savannah, Ga., and Georgetown and at points near the Santee River, and on the road from Georgetown to Charleston, but does not seem to have been felt at Columbia or Augusta, Ga.[16]

According to Gibbes a slight shock was recorded about October

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[13] *Year-Book of Charleston*, 1880, p. 314.

[14] From James Kershaw's Diary, published in Historic Camden by Thomas J. Kirkland and Robert M. Kennedy, Columbia, S. C., 1905, p. 410.

[15] King, William L. "The Newspaper Press of Charleston, S. C." Charleston, 1872, pp. 58-59.

[16] Gibbes, L. R. "Notice of Phenomena Attending the Shock of the Earthquake of December 19, 1857." *Proceedings Elliott Society*, Charleston, September 1, 1858, 1, 288-289.

1860,[17] and another slight shock is reported to have occurred on the evening of December 12, 1876.[18]

The earthquakes mentioned above probably had their origin in the area near Charleston, though owing to the lack of detailed information concerning the distribution of their intensities, this is not susceptible of absolute proof. Several additional earthquakes were recorded in the State prior to 1886, but the descriptions indicate that their origins must have been elsewhere than in the Charleston area, and therefore they are not listed here.

The catastrophe of August 31, 1886, was preceded by several slight preliminary tremors which, while they excited some comment at the time, caused no alarm and do not seem to have been generally understood. Near the end of June a slight shock was felt in Charleston accompanied by noise and the rattling of windows, but some thought that it was produced by a boiler explosion or the passing of wagons. At Summerville shocks were reported on August 27th, 28th and 29th, and some of these were felt by a few people in Charleston. When the first of these disturbances was reported many people in Charleston did not believe that an earthquake had occurred, and the newspapers of that day treated the subject with levity. These facts all indicate that earthquakes were of rare occurrence in this section prior to 1886.

In compiling the list of earthquakes felt since August 1886 the writer has made use of numerous publications and is indebted to many individuals for information courteously given. In the table on pages 150 to 160 the authority is given for each occurrence cited. Many of the shocks that occurred during 1886 are recorded in the files of the *Charleston News and Courier* but, unfortunately, after that year local earthquakes seem to have had no value as news items in so far as South Carolina newspapers were concerned. A list of the heavier shocks felt up to June 1887 was given by Mayor Courtenay in the *Charleston Year-Book* for 1886. In Dr. Manigault's account of the earthquake there is a table showing the number of shocks per day from August 27 to September 30, 1886.[19] Professor Mendenhall in his "Report on the Charleston Earthquake" published in the *Month-*

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[17] Gibbes, L. R. *Proceedings Elliott Society*, Charleston, July 1877, 2, 153-155.

[18] Rockwood, Jr., C. G. "Notices of Recent American Earthquakes," *American Journal Science*, 3, XV, pp. 21-27.

[19] "The Charleston Earthquake of August 31, 1886." Ninth Annual Report U. S. Geological Survey, 1889, p. 241.

ly Weather Review[20] lists the earthquakes recorded during September 1886, and Mr. J. H. Scott, Local Forecaster, furnished the writer with a copy of all the earthquake data recorded at the Charleston Weather Bureau Station since that date. Miss E. H. Gadsden, Cooperative Observer of the U. S. Weather Bureau at Summerville since July 1898, supplied a list of the shocks observed by her and also wrote a very clear description of the characteristics of these disturbances.[21]

It has been possible to check by independent observers many of the dates given in the lists mentioned above, and therefore, while they are by no means complete, their general accuracy can not be questioned. Several shocks given in the lists that were used in compiling the table of earthquake shocks (see pp. 150 to 160) have been omitted as they are known to have originated outside of the area now under discussion.

A study of all the earthquakes recorded proves that there has been a gradual though very irregular decrease in earthquake frequency since 1886, and that the decrease was most marked during the first half of this period. If a complete record were obtainable it would undoubtedly emphasize this decrease in seismic activity, for the records are more nearly complete for the last half of the period than for the first half. The number of shocks listed for the months immediately following August 1886 is very far short of the true number, for according to many contemporaneous accounts they were of almost daily occurrence at Summerville as late as the following March. Writing of the shocks felt on the night of August 31st, Mr. Thomas states that they were "nearly incessant for the first hour" and afterwards continued at the rate of twenty or forty per hour.[22]

Mr. J. B. Gadsden wrote: "All that night [August 31-Sept. 1] and for three days afterward the shocks continued, ten to fifteen minutes being the average length of time between each shock, and from that time up to this writing (Oct. 11, 1886) not one day or night has passed but we have been reminded of the terrors of that memorable night by numerous shocks, some slight, and others so severe as to cause us to leave our houses."[23]

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[20] Mendenhall, T. C. "Report on the Charleston Earthquake." *Monthly Weather Review*, August 1886, pp. 233-236.

[21] Without the generous assistance of Miss E. H. Gadsden and Mr. J. H. Scott this paper could not have been written. The writer desires to acknowledge his indebtedness to them and express his deep appreciation of the care and accuracy with which the data they furnished were recorded.

[22] Thomas, W. M. Statement published in *Proceedings Elliott Society*, July 1877, 2, 139-140.

The fact that no records of earthquakes have been obtained for the years 1889 and 1890 does not mean that none occurred; slight shocks and tremors were certainly felt at Summerville, if not in Charleston, during these years.

Dr. Manigault in discussing the aftershocks that occurred up to March 1887 states that "many occurred at Summerville which were scarcely felt in Charleston, and when they were noticed at both places they were usually more severe at Summerville."[24] An examination of the lists furnished by Miss Gadsden and Mr. Scott shows that seventy-five shocks have been recorded at Summerville since July 1898 as compared with only ten in Charleston. This is to be explained very largely by the fact that Charleston is at least twice as far from the locus of the disturbances as Summerville. Moreover, many slight tremors are necessarily overlooked in a large city because of the noise and vibrations due to the passage of trains and vehicles. Since February 1897 the office of the Weather Bureau in Charleston has been located in the Custom House, with railroad switches on two sides. In this connection it may be mentioned that the majority of the shocks recorded in Charleston were felt at night.

If we had complete seismic records for this area extending back through many thousand years, we would probably find that there have been occasional periods of relatively high seismicity, similar to that which has been in progress since 1886, separated by long periods of quiescence. If earthquakes are due chiefly to tectonic movements, then the relative seismicity of an area during a given period should be roughly commensurate with the amount of displacement experienced by the rocks during that period. In the Coast Ranges of California we find that sedimentary formations laid down as recently as Pliocene times have been folded and faulted during the process of mountain making, and that even the Pleistocene and Recent deposits show evidence of considerable movement; but, on the other hand, the beds of the Atlantic Coastal Plain dating back to the Cretaceous, exhibit almost no deformation and have been subjected to only small vertical movements, amounting to not more than a few hundred feet.

Compte Montessus de Ballore, by his extensive researches, established the close relation between earthquakes and regions of great terrestrial relief, and therefore the low relief of the Atlantic Coastal Plain may be taken as another fact indicative of relatively low seismicity.

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[23] Letter from Summerville, S. C., dated October 11, 1886.

[24] Manigault, G. E. "The Earthquake at Charleston." Ninth Annual Report U. S. Geological Survey, 1889, p. 241.

Thus, the evidence furnished by geology and physiography tends to show that, while there may have been occasional periods of earthquake activity, the seismicity of the Coastal Plain, as compared with other regions, has been relatively low since Cretaceous times—thousands and perhaps millions of years ago; and the great disturbance of 1886, with the numerous aftershocks continuing down to the present day, does not indicate that earthquakes are likely to be any more frequent in the future than they have been in the past.

PERIODICITY IN EARTHQUAKE FREQUENCY.

In order to determine whether there is any annual, semi-annual. or quarter-yearly periodicity in the earthquake frequency of this region the following table was compiled, and since the records are more nearly complete for the years 1898-1913 than for the years 1886-1897, the data are listed separately for each interval as well as for the entire period. In summing up the number of earthquakes, two or more separate shocks occurring within an interval of fifteen minutes are counted only once. The number of days on which earthquakes have occurred is also given, as in this way it is possible to reduce the influence of aftershocks that are really parts of a single disturbance.

Month	Number of Earthquakes			Number of Earthquake Days		
	1886-1897	1898-1913	1886-1913	1886-1897	1898-1913	1886-1913
January	18	8	26	10	8	18
February	12	4	16	8	4	12
March	18	11	29	15	11	26
April	5	1	6	5	1	6
May	7	7	14	6	7	13
June	24	7	31	17	7	24
July	26	1	27	14	1	15
August	46	6	52	22	6	28
September	78	15	93	34	15	49
October	30	4	34	17	4	21
November	27	5	32	17	5	22
December	27	8	35	15	8	23
Totals	318	77	395	180	77	257

Another reason for believing that the number of *earthquake days* rather than the number of shocks may possibly furnish a more accurate index to the relative seismicity of the different months, is that during the earlier years slight tremors often went unrecorded, especially when they occurred on the same day as disturbances of greater intensity. For the period 1898-1913 with its decreased seismicity the number of *earthquake days* is the same as the number of earthquakes. All of the data given in this table are shown graphically by means of diagrams on Plate 7.

The similarity of all these curves and especially of the three showing the number of *earthquake days* for each month is very striking, and indicates that they are probably for this district fairly accurate representations of the relative seismicity of the different months of the year. In every instance the maximum frequency falls in September with the minimum in April, and there is a well marked secondary maximum in March. While the list of *earthquake days* for the period 1886-1897 is necessarily incomplete, nearly all of the shocks recorded were felt in Charleston and were therefore of greater intensity than the tremors felt only near the origin. The general similarity between the curve for this period and the one for the years 1898 to 1913 is a fact strongly supporting the hypothesis that there is a true periodicity in the seismic activity of this region. The curve for the earlier period is of course strongly influenced by the train of aftershocks that occurred during the months immediately following the great disturbance of 1886, and therefore would be of questionable value if it were not for the fact that the curve for the later period is so closely similar. It has been impossible to classify all of the earthquakes according to their relative intensity and thus include this factor with that of frequency in the seismicity curves, but since the shocks are of more frequent occurrence after severe disturbances the general character of the curves would not be altered.

The curves were analyzed mathematically for annual, semi-annual and quarter-yearly periodicities, using the methods adopted by Dr. Knott,[25] and the results are tabulated below. This table shows that annual and quarter-yearly periodicities are more strongly marked than the semi-annual periodicity. The total number of earthquakes during the interval 1898-1913 is most too small to be of value in determining periodicities, but all of the results agree in placing the max-

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[25] Knott, C. G. "The Physics of Earthquake Phenomena." Oxford, 1908, pp. 106-114.

		Annual		Semi-Annual		Quarter Yearly		Expectancy
		Month of Maximum	Amplitude	Month of Maximum	Amplitude	Month of Maximum	Amplitude	
Earthquakes	1886-1897	Sept.-Oct.	0.491	Feb.	0.245	Mch.	0.214	0.099
Earthquakes	1898-1913	Oct.-Nov.	0.310	Feb.	0.278	Mch.	0.665	0.202
Earthquakes	1886-1913	Sept.-Oct.	0.607	Feb.	0.378	Mch.	0.455	0.089
Earthquake Days	1886-1897	Aug.-Sept.	0.333	Feb.	0.144	Mch.	0.194	0.132
Earthquake Days	1898-1913	Oct.-Nov.	0.310	Feb.	0.278	Mch.	0.666	0.202
Earthquake Days	1886-1913	Oct.-Nov.	0.401	Feb.	0.249	Mch.	0.457	0.110

imum for the annual periodicity in the autumn, for the semi-annual in the months of February and August, and for the quarter-yearly in March, June, September and December. As a result of Professor Schuster's application of Fourier's theorem to earthquake periodicities, Knott reached the conclusion that "when the amplitude reaches four times the expectancy the probability is so small that we are justified in regarding the existence of such an amplitude as evidence of a real periodicity." [26] There is probably no real semi-annual periodicity in the earthquake activity of this region. Annual and quarter-yearly periodicities are indicated though the data are most too meager to determine this question with certainty. However, the marked similarity of the different curves strongly supports the hypothesis that there are real annual and quarter-yearly periodicities.

RELATION OF RAINFALL TO EARTHQUAKE FREQUENCY

A close relationship between rainfall and earthquake frequency in this district is clearly indicated by every method of comparison that has proved possible of application.

Curves showing the normal monthly rainfall at Charleston and Summerville are given on Plate 7 for comparison with curves showing the monthly earthquake frequency. The normals for both towns are based upon the rainfall records of the U. S. Weather Bureau for the period extending from July 1898 to December 1913. This period is rather short for the accurate determination of monthly normals, but no earlier records are available for Summerville and it is highly desirable to compare the rainfall at the two places. A curve showing the normal monthly rainfall at Charleston and based upon records extending back to 1871 is similar to the one shown on Plate 7, except that it is smoother and the maximum falls in July instead of August, there being, however, a difference of only 0.29 inch of rainfall between the two months. The monthly normals computed for the longer period average 1.13 inches higher than those for the shorter interval.

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[26] Ibid., p. 114.

The rainfall curves for Charleston and Summerville are approximately parallel. Both show a strong maximum in August, one month prior to the seismic maximum in September; and both show a small secondary maximum in February, one month prior to the secondary seismic maximum in March. The normal rainfall at Summerville is greater than at Charleston for every month in the year; the greatest excess, 2.02 inches, occurring at the time of maximum precipitation in August. The normal annual rainfall at Summerville for the past fifteen years is 12.15 inches more than that at Charleston for the same period, giving an average difference of 1.01 inches per month.

Referring now to the curves showing annual rainfall and annual earthquake frequency (see Plate 8) it may be seen that while there is only slight evidence of relationship between the average rainfall for the state and the earthquake frequency, there is a very marked similarity between the earthquake curve and the Charleston rainfall curve.

The period of high seismic activity beginning in 1886 followed two years of unusually heavy precipitation which must have resulted in an important elevation of the water table. While the rainfall for 1886 was much lower than for the previous years, 86 per cent of it occurred prior to the earthquake in August, and during June 10.78 inches were recorded. The years of comparatively low rainfall between 1886 and 1891 are marked by a period of lower seismicity, while the year of heavy precipitation in 1893 coincides with a year of very high earthquake frequency. The period of great seismic activity occurring in 1893 began at 11:05 p.m. June 20th with a shock having an intensity of about VII R.-F., and during that month 16.50 inches of rain fell at Charleston, this being next to the highest record for any single month since the establishment of the Weather Bureau Station.

The yearly rainfall curve suggests no explanation for the relatively high seismicity of 1896, but when the monthly records are examined it is seen that the rainfall was above the average during the first few months of the year, while in June and July the precipitation was

7.57 and 10.58 inches respectively. Most of the earthquakes of that year occurred during August and September.

The heaviest precipitation for the past eighteen years was recorded in 1912 and there was a noticeable increase in the earthquake frequency for that year. Moreover, most of this rain fell during the first half of the year instead of in the last half as is customary, and on June 12th there occurred the severest earthquake experienced since 1893 and possibly since 1887.

During the period of high seismicity extending from 1886 to 1897 the average annual rainfall at Charleston was 52.17 inches, while during the period of relatively low seismicity from 1898 to date the average annual rainfall has been only 39 inches.

A graph showing the rainfall at Summerville for the past fifteen years is given on Plate 8, fig. 3, for comparison with the Charleston rainfall curve. The two curves are approximately parallel, the only departure occurring in 1908 when the precipitation at Summerville was much higher than at Charleston; and it is interesting to note that there was a slight increase in the seismicity for that year. The average rainfall at Summerville is almost one third greater than at Charleston, twenty miles away, and with few exceptions the amount of this difference varies directly with the precipitation.

The close relation apparently existing between the seismicity of this district and the local rainfall has been described in detail, and mention has been made of the very slight resemblance between the earthquake curve and the curve showing the average precipitation for the state, but when comparison is made with an average rainfall curve for the whole United States there is no evidence whatsoever of any possible connection.

Reference has been made to the fact that the average monthly rainfall at Summerville exceeds that at Charleston by more than one inch, and an examination of the monthly records for the past fifteen years shows that the difference in precipitation may amount to as much as four or five inches in a single month. As a result of heavy local showers it is easily possible to have a difference of one inch in the amount of rainfall at the two places in the course of a few hours, and this would mean a difference in the actual pressure applied to the earth's surface of over 72,000 tons per square mile.

In view of all the facts outlined above, there seems to be no escape from the conclusion that the local rainfall has been an important factor in determining the time of seismic disturbances in this particu-

PLATE 8.

Fig. 1. Mean tide level at Charleston for each year from 1885 to 1903, compiled from the records of the U. S. Army Engineers. The heights are referred to mean low water as established by the Engineers of the U. S. Army.

Fig. 2. Average total precipitation in South Carolina for each year from 1887 to 1913 based on the records of the U. S. Weather Bureau.

Fig. 3. Total precipitation at Summerville for each year from 1899 to 1913 based on the records of the U. S. Weather Bureau.

Fig. 4. Total precipitation at Charleston for each year from 1882 to 1913 based on the records of the U. S. Weather Bureau.

Fig. 5. The total excess of rainfall at Summerville over that at Charleston for each year from 1899 to 1913, computed from the records of the U. S. Weather Bureau.

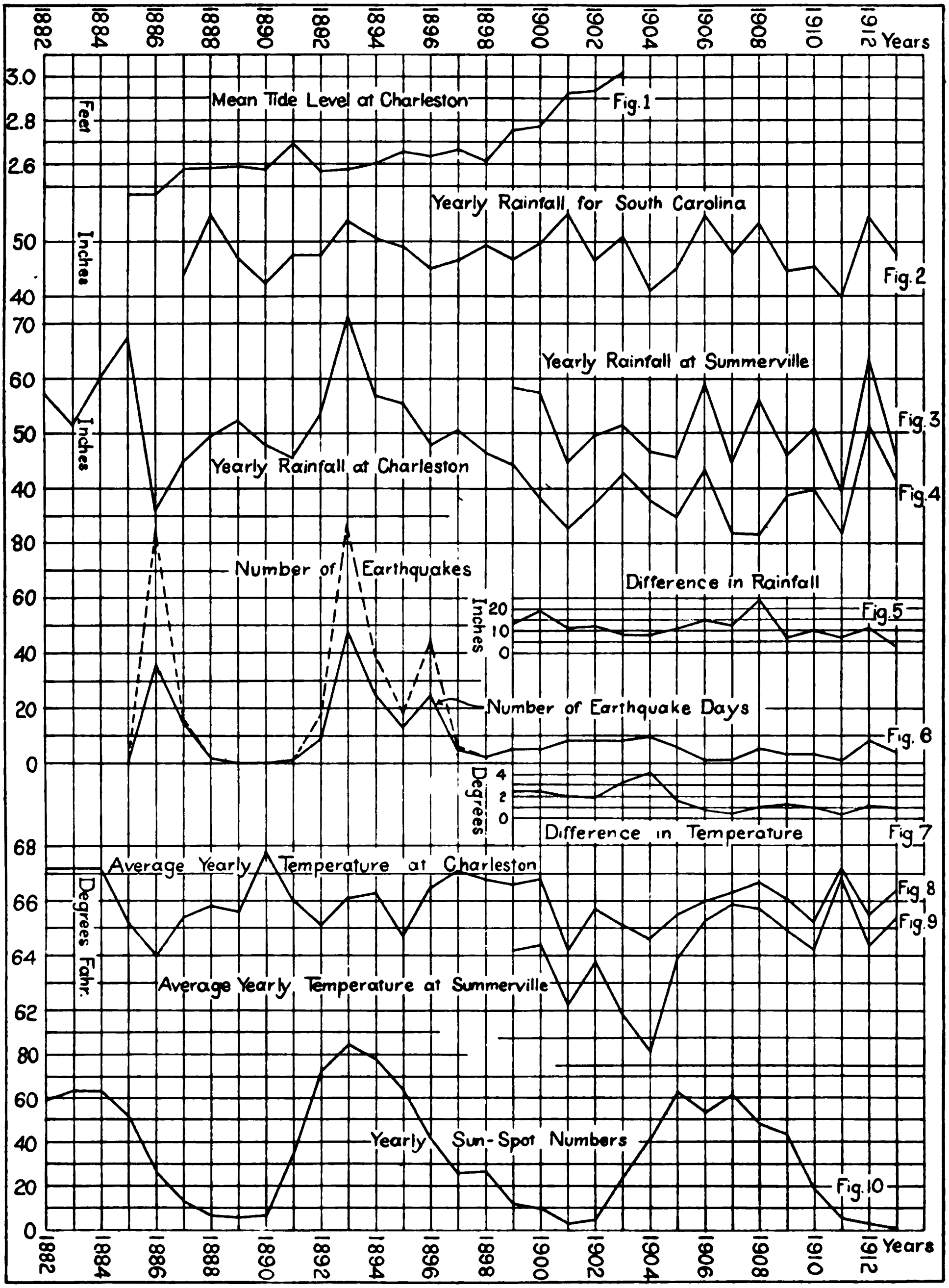
Fig. 6. The dotted line shows the total number of earthquakes recorded each year from 1885 to 1913. The full line shows the total number of days on which earthquakes were recorded each year from 1885 to 1913.

Fig. 7. The difference in the average yearly temperatures at Charleston and Summerville (the temperature at Charleston being the higher) for each year from 1899 to 1913, computed from the records of the U. S. Weather Bureau.

Fig. 8. Average temperature at Charleston for each year from 1882 to 1913 based on the records of the U. S. Weather Bureau.

Fig. 9. Average temperature at Summerville for each year from 1899 to 1913 based on the records of the U. S. Weather Bureau.

Fig. 10. Wolf's sun-spot numbers for each year from 1882 to 1913.


1882
1884
1886
1888
1890
1892
1894
1896
1898
1900
1902
1904
1906
1908
1910
1912
Years
3.0
2.8
2.6
Feet
Mean Tide Level at Charleston
Fig. 1
Yearly Rainfall for South Carolina
50
40
Inches
Fig. 2
70
60
50
40
Inches
Yearly Rainfall at Summerville
Fig. 3
Yearly Rainfall at Charleston
Fig. 4
80
60
40
20
0
Number of Earthquakes
Difference in Rainfall
Inches
20
10
0
Fig. 5
Number of Earthquake Days
Fig. 6
Degrees
4
2
0
Difference in Temperature
Fig 7
68
66
64
62
Degrees Fahr.
Average Yearly Temperature at Charleston
Fig. 8
Fig. 9
Average Yearly Temperature at Summerville
80
60
40
20
0
Yearly Sun-Spot Numbers
Fig. 10

lar district; there is, however, no ground for the assumption that the same relation holds true in all other areas, and in fact there is every reason to suppose that with different conditions the relation between rainfall and earthquake frequency might even be reversed. Increase in the local rainfall is usually accompanied by an increase in the amount by which the rainfall at Summerville exceeds that at Charleston, and it is probably due to this fact that the seismic activity varies with the rainfall.

A comparative study of rainfall records and earthquake frequency in the Charleston area shows that the periods of high seismic activity follow rather than coincide with the periods of heavy rainfall. This is probably explained in part by the fact that the pressure resulting from a moderate rainfall together with that of a high water-table may often be greater than the pressure due to a heavy rainfall combined with a low water-table. It is likely, however, that there is more or less lag, and that in many cases the readjustment of strains with resulting earthquakes takes place a short while after the greatest strain has been reached. The data at present available indicate that long continued periods of rainfall are more closely associated with increased seismic activity than short periods of very heavy precipitation.

RELATION OF GROUND-WATER TO EARTHQUAKE FREQUENCY

If, as there is every reason to believe, relative surface pressure is at all influential in determining the time of vertical displacements along faults, then the fluctuations in the height of the water-table are of the utmost importance in this connection; but at present no detailed observations are available concerning these fluctuations at any point in the South Atlantic States.

The underground waters of the Coastal Plain are of course derived directly from the rainfall, and, as a result of the low relief and sandy soils in the region near Summerville and Charleston, an unusually high percentage of the water falling on the surface, perhaps ninety per cent, sinks into the ground. The remainder either returns to the atmosphere through evaporation or runs off to the sea on the surface. The water that enters the ground migrates downward until it joins the vast supply of underground water that saturates the formations of the Coastal Plain to within a relatively short distance of the surface. The upper limit of this underground water is known as the water-table. The water-table is roughly parallel to the surface, excepting that it is less irregular, being farther from the surface under the hills and nearer to it under the valleys, while in low places where it reaches the surface, there are ponds and swamps. Near Charleston the water-table is of course closer to the surface on the average than it is at Summerville, and swampy areas become less extensive with distance from the coast. During long periods of excessive rainfall the water-table rises; during corresponding periods of drought it subsides. Its subsidence is due to many causes, the most important of which are the slow lateral movements which return part of the water to the surface through springs and evaporation, including plant transpiration. Changes in the height of the water-table, due to the acceession of rainwater, are not sudden, for it takes a sensible period for the soil to absorb and transmit rainfall; therefore the water in wells may be low during a period of rainy weather in consequence of preceding drought, and it usually remains high long after rains have ceased. As a result of the low relief springs are rare in this region, and evaporation is by far the most important factor operating to lower the height of the water-table.

Since evaporation varies with the temperature, there is a regular annual fluctuation in the height of the water-table due to this cause, aided by the increased transpiration of plants during the months when they are in foliage. The water-table is highest in the spring months, there being much water standing on the surface in swamps and low places; it is lowest in late summer and autumn, when many of the swamps are dry and the water in open wells is low. Therefore in this region the actual pressure per unit area of the earth's surface must be greatest in the spring when seismic activity is relatively low, and least in the autumn when the seismic activity attains its maximum. This proves, for this district at least, that mere increase of surface pressure does not result in any greater frequency of earthquakes.

In the absence of detailed information concerning ground-water fluctuations, any conclusions as to variation in relative pressure on opposite sides of the assumed fault, caused by variation in the height of the water-table, must be deduced from the known facts regarding rainfall and evaporation.

The normal monthly temperature and the normal monthly rainfall for both Charleston and Summerville are shown together by means of graphs on Plate 7 so that they may be compared readily. The averages used in plotting these curves are based on the records of the U. S. Weather Bureau for the past fifteen years. The average rainfall at Summerville is almost one third greater than it is at

Charleston, but the difference in the amount of rainfall at the two places is not evenly distributed throughout the year. The average difference in rainfall for the first eight months of the year is 1.20 inches, the maximum, 2.02 inches, occurring in August; while for the last four months the average difference in monthly rainfall is only 0.62 inch. This must result in an increase in the pressure at Summerville relative to the pressure at Charleston during the months of heaviest rainfall, unless the withdrawals from the ground-water supplies at each place vary in such a manner as to compensate for the unequal additions due to difference in rainfall, but this is almost inconceivable. If the amounts of water removed from the underground reservoirs were constant, during the summer months there would be a gradual increase in the pressure at Summerville relative to the pressure at Charleston, which would reach a maximum in August.

The normal temperature for the year is 1.7° F. higher at Charleston than at Summerville. The mean daily range of temperature is much greater at the latter station. The difference between the normal monthly temperatures at the two places increases gradually from a minimum of 0.2° in March to a maximum of 2.8° in November, and therefore if other conditions were equal the difference in the amounts of water evaporated at Summerville and Charleston would be least in March and greatest in November; but there are other factors which tend to advance the time of maximum difference in the amounts of water evaporated at the two places. Near the coast the water-table is closer to the surface than it is farther inland, and in the spring when it is highest there is more water standing on the surface; hence, during the first warm months, probably more water is evaporated per unit area near Charleston than in the vicinity of Summerville. The amount of water lost by seepage varies with the height of the water-table, which in turn is controlled chiefly by the rainfall and evaporation.

All the facts developed by a careful study of the question indicate that the pressure resulting from the position of the water-table is relatively greatest on the northwest side of the assumed fault at the time of or just prior to the seismic maximum in September.

Fluctuations in the height of the water-table are necessarily much greater at Summerville than at Charleston, because of the greater relief and heavier rainfall at the former place; and, as the water-table on the average is much closer to the surface near the coast than it is farther inland, the underground storage capacity above the normal ground-water level is greater near Summerville than in the vicinity of Charleston. For this reason a prolonged period of heavy rainfall must result in a relatively greater rise in the water-table on the northwest side of the assumed fault. This probably explains the increase in seismic activity after years of unusually heavy precipitation. A graph showing the average temperatures at Charleston for each of the years 1882-1913 is given on Plate 8, fig. 8, and while at a glance it shows little resemblance to the earthquake curve, it is significant that the lowest average temperature recorded for any year since the beginning of observations in 1871 occurred in 1886, and that the periods of high seismicity in 1893 and 1896 were each immediately preceded by years with average temperature well below normal. Of course the effect of these periods of low temperature is to raise the water-table.

The annual rainfall and temperature graphs for Summerville are given on Plate 8 for comparison with the others, but unfortunately the records for this station cover only the last fifteen years. Each year the average temperature at Charleston exceeds that at Summerville, and the amount of this excess apparently varies inversely as the temperature. The annual rainfall at the two stations has already been compared. Fluctuations in the position of the water-table at Summerville relative to the water-table at Charleston are largely due to variations in the difference in rainfall and variations in the difference in temperature between the two places. For this reason curves showing the annual difference in rainfall and the annual difference in average temperature are given for comparison with the annual seismicity curve. (See figs. 5 and 7, Plate 8.) The general parallelism between the seismicity curve and the curve showing the annual difference in average temperature is remarkable, and when the three curves are considered together there can be no doubt but that the relative position of the water-table has been an important factor in determining earthquake frequency.

During the years 1899-1905 the average difference in temperature was 2.51° F., and the average earthquake frequency 7 shocks per year; during the period 1906-1913 the average difference in temperature was only 0.85° F., and the average earthquake frequency 3.25 shocks per year. For the last fifteen years the greatest difference in temperature, 4.1° F., and the maximum earthquake frequency both occurred in 1904. After that year the seismicity curve and the curve showing annual difference in average temperature decrease to a minimum in 1906 and 1907, and then they rise together in 1908;

they both show another minimum in 1911, rise in 1912, and fall again in 1913. The small seismic maximum in 1908 does not coincide with a large difference in temperature, but during this year the rainfall at Summerville was very much greater than at Charleston. (See fig. 5, Plate 8.)

Every fact brought out by a detailed examination of all available data indicates that the earthquake frequency increases directly with any factor tending to raise the relative height of the water-table on the northwest side of the assumed fault. Therefore, there seems to be no escape from the conclusion that the seismicity of the district increases with any increase in the relative surface pressure on the northwest side of the fault, because of fluctuations in the relative height of the water-table in the region on either side. It is an important fact that there is no increase in earthquake frequency with increase in the total pressure applied to the area, but that the earthquake frequency increases only with an increase in the surface pressure on the northwest side of the fault relative to the pressure on the opposite side.

RELATION OF ATMOSPHERIC PRESSURE TO EARTHQUAKE FREQUENCY

Atmospheric pressure is probably the next most important factor in determining the time of seismic disturbances in this region. By consulting the daily maps of the U. S. Weather Bureau for the period 1898 to 1913, it was ascertained that forty-three of the earthquakes occurred on days when in the vicinity of Charleston the barometric gradient decreased toward the southeast and increased toward the northwest; only fifteen shocks occurred on days when the gradient sloped in the opposite direction; and the other seventeen shocks were on days when the barometric gradient was very slight or could not be determined. This means that for the *earthquake days* on which the barometric gradient was determinable 74 per cent occurred when the atmospheric pressure was greatest on the northwest side of the supposed fault-line, and only 26 per cent when the pressure was least on that side.

For the years 1886-1897 the daily weather maps were not available, and therefore a list of the days on which earthquakes were recorded was sent to the Director of the U. S. Weather Bureau with a request for the information. According to the data furnished, twenty-seven shocks occurred on days when the barometric gradient sloped toward the southeast, and only one shock occurred on a day with the gradient sloping in the opposite direction, while for the remainder of the days the gradient could not be determined. The ratio of 27 to 1 is very striking, though the large number of days on which it was not possible to determine whether the atmospheric pressure increased or decreased in a northwest-southeast line is certainly excessive. Not having had access to the daily weather maps for that period the writer can offer no explanation unless, possibly, it is due to the fact that fewer details are shown on the earlier maps.

All of the evidence available indicates that the barometric gradient is probably an important factor in determining the time of earthquake disturbances in this district.

An investigation was also made to ascertain whether or not there was any relation between earthquake frequency and the actual amount of atmospheric pressure. The 8 a.m. barometric readings at Charleston reduced to sea level were obtained for each day on which earthquakes were recorded, and after being reduced to the 24-hour mean were compared with the normal pressure for the month in which the day occurred. The normals are based on an eighteen-year period.

During the period 1898-1913 the atmospheric pressure on *earthquake days* was above normal for 58 per cent of the days, below normal for 41 per cent, and normal for 1 per cent. During the period 1886-1897 the percentages were above normal 61, below normal 37 and normal 2. An examination of the daily weather maps suggests that there are probably more days when the atmospheric pressure was above normal than below normal, for the isobars are apt to be much closer together about areas of extreme low pressure than they are about areas of high pressure. In order to obtain quantitative data on this question, the 8 a.m. sea-level barometric pressures at Charleston for every day during the four years, 1910-1913, were taken from the records accompanying the daily weather maps, and reduced to the 24-hour mean. These figures were then compared with the normal sea-level pressure for the month in the same way as for days on which earthquakes occurred. It was found that the atmospheric pressure was above normal on 55 per cent of the 1461 days and below normal on 43 per cent of the days. A comparison of these percentages with those given above for *earthquake days* indicates that earthquakes are almost as frequent on days with atmospheric pressure below normal as on days when it is above normal.

A graph (see Plate 9, fig. 3) plotted to show the relation between earthquake frequency and atmospheric pressure is fairly smooth and regular, the largest number of earthquakes occurring on days

PLATE 9.

Fig. 1. Distribution by hours of the earthquakes recorded during the period 1886-1913.

Fig. 2. Mean hourly barometric pressure at Savannah, Ga., reduced to sea level. The data used in plotting this curve were computed from the records of the U. S. Weather Bureau for the period 1891-1904.

Fig. 3. A curve showing the number of recorded *earthquake days* that had various departures from normal barometric pressure during the period 1886-1913.

Fig. 4. A curve showing the relative number of days having various departures from normal barometric pressure during the period 1910-1913. The scale used in plotting this curve was taken as 1/6.25 of that used for the previous diagram so that the curves could be compared the more readily.

Fig. 5. A curve showing variations in earthquake frequency according to the day of the anomalistic month during the period 1886-1913.

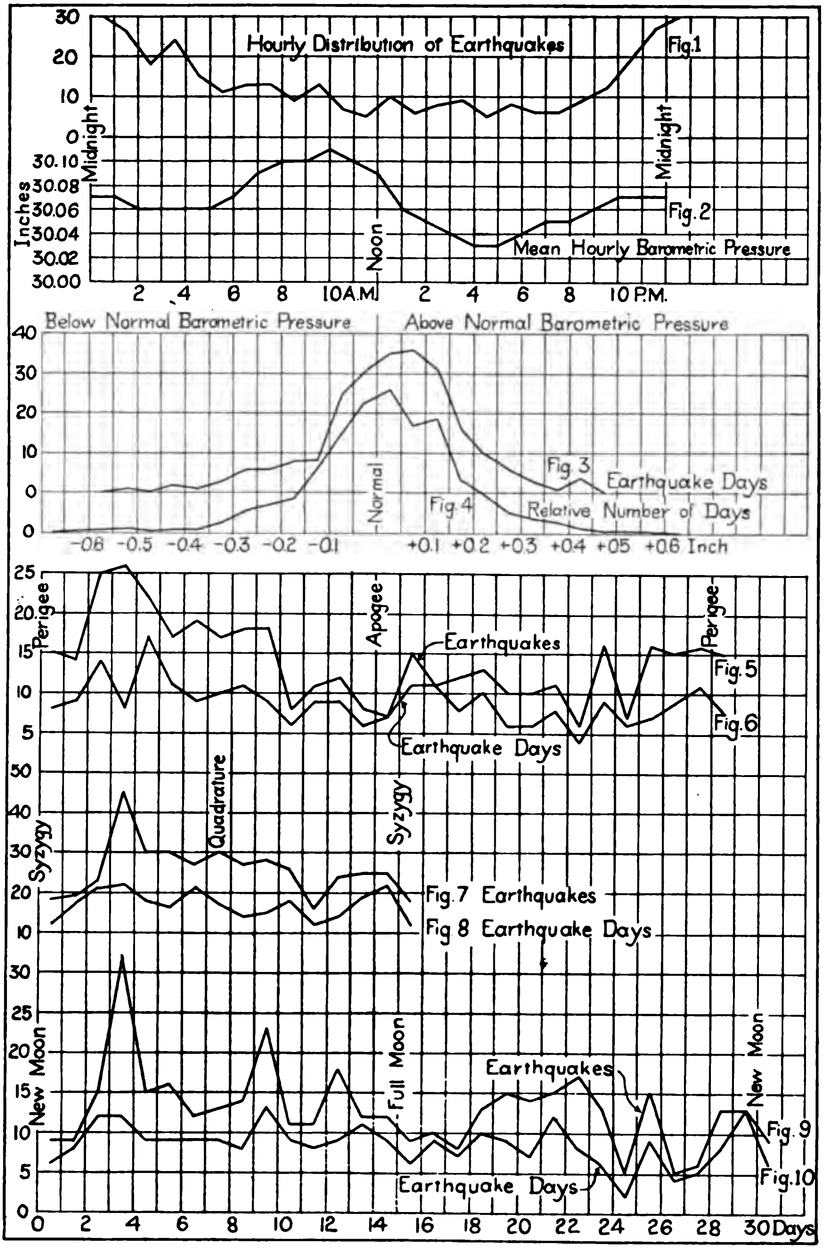
Fig. 6. A curve showing variations in the frequency of *earthquake days* according to the day of the anomalistic month during the period 1886-1913.

Fig. 7. A curve showing semi-monthly (synodic month) variations in earthquake frequency during the period 1886-1913.

Fig. 8. A curve showing semi-monthly (synodic month) variations in the frequency of *earthquake days* during the period 1886-1913.

Fig. 9. Monthly (synodic month) variations in earthquake frequency during the period 1886-1913.

Fig. 10. Monthly (synodic month) variations in the frequency of *earthquake days* during the period 1886-1913.


Hourly Distribution of Earthquakes
Fig.1
30
20
10
0
Midnight
Midnight
Noon
30.10
30.08
30.06
30.04
30.02
30.00
Inches
Fig. 2
Mean Hourly Barometric Pressure
2
4
6
8
10 A.M.
2
4
6
8
10 P.M.
Below Normal Barometric Pressure
Above Normal Barometric Pressure
40
30
20
10
0
0
Normal
Fig. 3
Earthquake Days
Fig. 4
Relative Number of Days
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
+0.1
+0.2
+0.3
+0.4
+0.5
+0.6 Inch
25
20
15
10
5
Perigee
Apogee
Perigee
Earthquakes
Fig. 5
Fig. 6
Earthquake Days
50
40
30
20
10
Syzygy
Quadrature
Syzygy
Fig. 7 Earthquakes
Fig 8 Earthquake Days
30
25
20
15
10
5
0
New Moon
Full Moon
New Moon
Earthquakes
Fig. 9
Earthquake Days
Fig. 10
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30 Days

when the barometer registered between 0.05 and 0.10 inch of mercury above normal. A curve (see Plate 9, fig. 4) showing the relative number of days having various atmospheric pressures is given for comparison; and inspection shows the two curves to be closely similar, thus supporting the hypothesis that the time of earthquake shock is in no wise controlled by the degree of atmospheric pressure when evenly distributed over the area. This hypothesis is further confirmed by a study of the annual and diurnal variations in atmospheric pressure.

The normal sea-level barometric pressure at Charleston for each month of the year,[27] based on the records for the period 1873-1900, is shown graphically on Plate 7, fig. 12. This curve shows absolutely no resemblance to any of the seismicity curves. The greatest atmospheric pressure occurs in January, while the seismic maximum falls in September; and neither the annual, the semi-annual, nor the quarter-yearly periods in earthquake frequency show a maximum in January.

Records are not obtainable for computing the normal sea-level pressure at Charleston for the hours of the day, but these data are available for Savannah, Ga.,[28] and there the pressure should be practically the same, for the location is similar and the two places are not more than ninety miles apart. The curve showing the mean barometric pressure for the hours of the day at Savannah (see Plate 9, fig. 2) has a maximum at 10 a.m. and a minimum at 4 p.m. with a smaller maximum at midnight and corresponding minimum at 3 a.m. In contrast the curve showing hourly variations in earthquake frequency rises rapidly to a maximum at midnight and then decreases gradually with but small irregular fluctuations. The greater frequency of earthquakes at night is probably exaggerated by the fact that many small tremors pass unnoticed amid the activities and noises of the day. If the greater frequency of earthquakes at night is in any way caused by atmospheric pressure it is probably due to the relatively greater pressure over the land at night and over the sea in the day time. In other words, the barometric gradient tends to slope southeastward toward the ocean at night and in the opposite direction during the day.

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[27] These data are given by F. H. Biglow in the "Report on Barometry," in Report of the Chief of the Weather Bureau, 1900-1901, 2, 453.

[28] The data used in plotting this curve were computed by the writer from a table, furnished by Mr. J. P. Slaughter, Local Forecaster, giving the average hourly barometric pressure at Savannah, Ga., for each month for the years 1891 to 1904 inclusive.

A consideration of all the evidence as to the relation between atmospheric pressure and earthquake frequency in this region indicates that there is probably no connection between high and low pressure and earthquake activity, but that the shocks are most likely to occur when there is a barometric gradient sloping southeast. Thus a detailed study of atmospheric pressure and its possible effect on seismic activity in the region near Charleston supports the hypothesis that earthquakes are most likely to occur at times when the surface pressure is relatively greatest on the northwest side of the assumed fault.

RELATION BETWEEN HEIGHT OF SEA LEVEL AND EARTHQUAKE FREQUENCY

In the immediate vicinity of the shore line the earth's crust is subjected to periodic strains of considerable magnitude, due to variation in the relative height of sea level, but it is not known how far from the coast these strains extend. It is a fact of some importance in this connection that, near the ocean, the height of the water-table and the pressure in artesian wells commonly fluctuate with variations in the height of sea level. At Charleston, in wells with a depth of over a thousand feet and also in wells that are not more than sixty feet deep, the water level has been observed to oscillate from four to six inches at regular tidal intervals.[29]

The mean relative height of sea level at Charleston for each month in the year[30] is shown by graph on Plate 7, fig. 12, where comparison may be made with the corresponding seismicity curve, but there is no apparent relation between the monthly variations in sea level and the earthquake frequency. An inspection of the curve showing normal sea-level barometric pressure at Charleston for each month of the year suggests that atmospheric pressure has probably been the most influential factor controlling the annual variations in mean sea level.

The most important of the periodic fluctuations in height of sea level, however, are due to the semi-diurnal tides. A list of earthquake shocks was sent to the Superintendent of the U. S. Coast and Geodetic Survey, who kindly supplied the writer with the time of the nearest high water for each of the shocks recorded. For 96 shocks the time of nearest high water was observed, while for 257 only the predicted time of high water was available. From these data it is possible to determine the relative number of shocks that have occurred during stated intervals before high tide, and this information is shown graphically on fig. 2. A careful examination of the curve shows that the times of earthquake shocks are distributed without reference to the hours of high and low water; and when it is tested mathematically for a harmonic periodicity, the maximum number of shocks is found to occur about seven hours and the minimum about one hour before high water, but the amplitude is less than twice the expectancy. This proves that the tides have had little if any influence in determining the time of earthquake shocks. It is interesting, however, to note that the slight maximum occurs near the time of low water, that is to say, when the effect of sea-level height is to reduce to a minimum the load on the southeast side of the assumed fault.

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[29] "Artesian Wells—Report of Special Committee," Year Book of the City of Charleston, 1881, p. 272.

[30] All of the sea level data used in this investigation were furnished through the courtesy of the Superintendent of the U. S. Coast and Geodetic Survey.

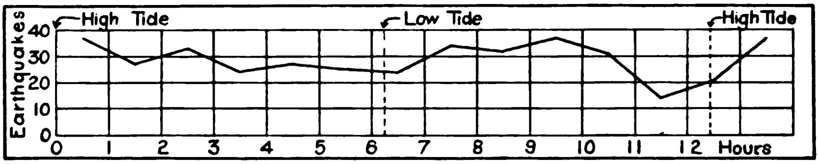

Fig. 2.—Relation between earthquake frequency and the tides at Charleston, S. C., based on the period, 1886-1913.

The distance of the fault from the sea coast is possibly the explanation of the fact that tides seem to have little or no influence in determining the time of shock. The distribution of intensities at the time of the earthquake in 1886 indicates that the fault is located at least eighteen miles from the ocean near Charleston. The triangulation surveys made in California, in the vicinity of the San Andreas fault, before and after the displacement resulting in the earthquake of 1906, show that the distortion of the rocks was limited to a distance of probably less than six miles on either side of the fault.[31] The crystalline rocks, underlying the Coastal Plain formations in South Carolina, are presumably more rigid and elastic than the rocks cut by the California fault, but even then, it is improbable that the fluctuations in tide level are able to produce important changes in the amount of stress at a distance of eighteen miles inland. In the Cooper and Ashley rivers the tidal influence is noticeable for a distance of thirty-five to forty miles from Charleston, but the area covered by these waters is so small, compared with the land area, that the tides must be unimportant in changing the surface pressure over the area as a whole.

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[31] Reid, H. F. "The Mechanics of the Earthquake." California Earthquake of April 18, 1906, **2**, 25.

A table giving the mean sea level for Charleston Harbor for each year from 1885 to 1903, compiled from the records of the U. S. Army Engineers, was furnished by the Superintendent of the U. S. Coast and Geodetic Survey. These data are plotted in fig. 1, on Plate 8. The heights are referred to mean low water as established by the Engineers of the U. S. Army, but because of insufficient notes concerning the relation of the automatic gauge to a uniform datum, there is a degree of uncertainty in these values.

With some minor irregularities there has been a gradual rise of mean sea level from 2.46 feet in 1885 and 1886 to 3.08 feet in 1903.

Unfortunately, no reductions are available for the years since 1903, and therefore it is impossible to determine whether the movement continues in the same direction, or whether, as has been observed elsewhere, it reached a maximum and then gradually subsided. The length of the period during which the movement continued in the same direction indicates that the change in sea level was due to an actual depression of the land rather than to changes in the atmospheric pressure over the ocean. It is suggestive that the period of relatively low mean sea level prior to 1898 coincides with a period of relatively high seismicity, while during the early part of the period of low seismicity beginning in 1898, there was a rapid rise in the height of mean sea level. For the thirteen-year period from 1885 to 1898 the rise in mean sea level amounted to only 0.15 foot, while during the five years following 1898 the rise was 0.47 foot. Of course the effect of high water is to increase the relative load on the southeast side of the supposed fault, while low water decreases the load.

In summarizing the results obtained from a careful study of semi-diurnal, annual and mean annual fluctuations in height of sea level at Charleston and their possible relation to seismic activity, it may be said that there is very little evidence of any relation between height of sea level and earthquake frequency, but such evidence as there is tends to support the theory that earthquakes are more likely to occur at times when the surface pressure is relatively greater on the northwest side of the assumed fault near Woodstock.

RELATION OF SUN-SPOTS TO SEISMIC ACTIVITY

Investigations have been made by Jensen, Sayles and Huntington for the purpose of determining whether there is any relation between sun-spot frequency and the volcanic and seismic activity of the earth as a whole, but no attempt seems to have been made to connect the earthquake activities of a single district with the occurrence of sun-spots. The data collected by Jensen and Sayles and published by Huntington [32] indicate that volcanic and seismic activity is at a maximum during periods of minimum sun-spots and at a minimum during periods of maximum sun-spots. Later investigations led Sayles to believe that the relation existed between volcanic action and sun-spots rather than between earthquakes and sun-spots.[33]

The sun-spot curve is given on Plate 8 for comparison with the seismicity curve of the South Carolina district. The sun-spot numbers for the years prior to 1908 were taken from the table in the Encyclopædia Britannica,[34] and the numbers for the later years were furnished by Dr. C. G. Abbott. He states that "the numbers for 1912 and 1913 are provisional numbers, and for 1913 the value is based on the first nine months only." [35] A careful inspection of the curves fails to show any evidence of relationship between the earthquake frequency in this region and the occurrence of sun-spots. It is probably only a coincidence that the year 1893 was a year of maximum sun-spots and of maximum earthquake frequency, for the other years of marked seismic activity are in no way connected with sun-spot maxima.

RELATION BETWEEN EARTHQUAKE FREQUENCY AND LUNAR PERIODICITIES

Many attempts have been made to correlate lunar periodicities with the earthquake frequency of individual districts and of the earth as a whole; but, with the accumulation of accurate statistics, it has been shown that the attraction exerted by the sun and moon on the earth's surface has little if any influence in determining the time of earthquakes. Logically no other conclusion could be expected in the case of tectonic earthquakes, for the attraction of the sun and moon is uniformly distributed over large areas of the earth's surface, and therefore can directly cause very little difference in the stresses on opposite sides of faults. Since the oceanic tides are due to the attraction of the sun and moon, and tidal loading of the surface near the coast line does produce differential stresses, the position of the heavenly bodies relative to the earth may indirectly result in the development, in coastal regions, of stresses sufficient in magnitude to control the time of fault displacements. The ratio of the height of spring tides (when the moon is in syzygy) to the height of neap tides (when the moon is in quadrature) is as 7 is to 4; and the tides are 20 per cent higher when the moon is in perigee than when in apogee. For this reason it was decided to investigate and determine if possible whether there was any relation between the occurrence of earthquakes in this region and the position of the sun and moon relative to the earth.

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[32] Huntington, E. "Coincident Activities of the Earth and the Sun." *Popular Science Monthly*, **72**, 1908, 492-502.

[33] Personal communication from Dr. R. W. Sayles, June 26, 1913.

[34] Encyclopædia Brittanica (11th edition), 1910, **2**, 931.

[35] Personal communication from Dr. C. G. Abbott, Director of the Astrophysical Observatory, Smithsonian Institution; January 8, 1914.

The Superintendent of the U. S. Naval Observatory kindly furnished the writer with the dates of perigee and of new moon for the various months in which earthquakes have been recorded. From these data it is possible to compute the number of earthquakes and the number of *earthquake days* that have occurred on successive days after new moon and after perigee. These data are shown graphically on Plate 9. When these curves are tested mathematically for monthly and semi-monthly periodicities it is seen that in each curve the amplitude does not greatly exceed the expectancy. We must therefore conclude that in this district there is no relation direct or indirect between the attraction of the sun and moon and the time of earthquake disturbances.

CHARACTERISTICS OF THE EARTHQUAKES

The earthquake shocks that have occurred in the region near Charleston, S. C., have certain peculiarities that serve to distinguish them from the similar disturbances of some other districts; and these peculiarities are, for the most part, explainable on the basis of geologic structure.

The most striking characteristic of these earthquakes is the extent of the area within which the disturbances are perceptible, considering the relatively low intensity shown in the epicentral region, and this is especially noticeable in the case of the heavier shocks. The following table, compiled by Tarr and Martin, gives the areas affected by some of the greater tectonic earthquakes of historic times.[36] It is seen that among all the earthquakes listed the Charleston Earthquake of 1886 ranks first in area affected, and yet the detailed investigations of the effects of the shocks, as well as the descriptions of numerous observers, indicate that the maximum intensity in the epicentral region was low

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[36] Tarr, Ralph S., and Martin, Lawrence. "The Earthquakes at Yakutat Bay, Alaska, in September, 1899." Professional Paper U. S. Geological Survey, No. 69, 1912, p. 128.

Center	Date	Approximate Area Affected
Lisbon, Portugal	1755	[a]2,240,000 square miles
New Madrid, Mo.	1811-1812	1,250,000 " "
Charleston, S. C.	1886	2,800,000 " "
Riviera	1887	219,000 " "
Sonora, Mexico	1887	500,000 " "
Mimo-Owari, Japan	1891	330,000 " "
Assam, India	1897	1,750,000 " "
Yakutat Bay, Alaska	1899	1,539,000 " "
Kangra, India	1905	1,500,000 " "
San Francisco, Cal.	1906	372,700 " "

[a] Perhaps 500,000 square miles less; Oldham (Mem. Geol. Survey India, **29**, 376) says perhaps only 1,000,000 square miles.

as compared with the other great earthquakes. There were no marked superficial changes such as accompanied the earthquakes of New Madrid in the Mississippi Valley; Mimo-Owari, Japan; Assam, India; Yakutat Bay, Alaska; and California. It is true that in the epicentral area the ground was broken by many fissures, through which water issued bringing up sand and building it into craterlets; but, as already explained, this was due to geologic structure rather than extreme intensity of shock, for the region is underlaid with unconsolidated sediments saturated with water, and in places quicksand is present only a few feet below the surface. Dutton states: "The fissures seldom attained a width of more than an inch, excepting in the vicinity of river banks, where an actual movement of the banks toward the channel of the river opened exceptionally wide cracks parallel to the river side. Elsewhere the widths of the fissures were seldom as great as one inch."[37] During the California earthquake of 1906 fissures having a maximum width of five feet were formed near the Coyote River, fifteen miles from the fault, and their origin is attributed to the unstable condition of the alluvial deposits underlying the Santa Clara Valley.

The damage to the buildings at Summerville and Lincolnville, the only villages within the epicentral tract, was not such as to indicate a very high intensity. The houses in Summerville were of wood, and supported on small piers either of wood or of brick, five to seven feet in height. This type of foundation is poorly adapted to resist severe earthquake shock, and yet, while the majority of the houses moved on their supporting pillars, only eight of them fell and were badly wrecked. Dutton thought that this indicated a direction of motion more nearly vertical than horizontal.[38]

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[37] Dutton, C. E. "The Charleston Earthquake of August 31, 1886." Ninth Annual Report U. S. Geological Survey, 1889, p. 281.

A careful examination of all available evidence has failed to disclose any fact indicating that the intensity of shock anywhere in the epicentral tract of the Charleston earthquake was comparable with that shown in the immediate vicinity of the San Andreas fault during the California earthquake. At the time of the latter disturbance the vibrations within a belt extending not more than 400 or 500 yards on each side of the fault, were sufficiently violent to uproot oak trees six feet in diameter and break off sound limbs two feet thick.[39]

The earthquake of June 12, 1912 (see map, fig. 3, on p. 146) had an intensity of VI R.-F. at Charleston and of about VII at Summerville near the origin, but the shock was sensible over an area of at least 130,000 square miles. For purposes of comparison, it may be mentioned that the earthquake which occurred in Union County, South Carolina, on January 1, 1913, had an intensity of over VIII near the origin and was sensible over an area of only about 43,000 square miles.[40]

The amount of energy set free per unit area of the fault-plane must have been much greater for the Charleston earthquake of 1886 than for the California earthquake, because the displacement along the fault near Charleston, which could not have extended much over twenty-five or thirty miles, affected an area of 2,800,000 square miles, whereas the California fault-line was ruptured for at least 270 miles and the area affected was only 372,700 square miles.

Since the intensity per unit area of the fault-plane must have been great, the relatively low intensity observed in the epicentral region of the Charleston earthquake is probably to be explained by the depth of the fault-plane below the surface and the great thickness of the overlying unconsolidated sediments. In California the fault extended to the surface, and in few places were the solid rocks covered by more than a few hundred feet of alluvial material; near Charleston, the crystalline rocks, within which the disturbances originate, are buried under sedimentary deposits one half mile in thickness.

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[38] Ibid., pp. 273-276.

[39] Taber, Stephen. "Some Local Effects of the San Francisco Earthquake," *Journal of Geology*. **14**, 311.

[40] Taber, Stephen. "The South Carolina Earthquake of January 1, 1913." *Bulletin Seismological Society of America*, **3**, 12, 1913.

The Charleston earthquake was felt at La Crosse, Wis., a distance of 990 miles at right angle to the assumed fault; whereas Winnemucca, Nev., 350 miles at right angle to the fault-line, was the farthest point at which the California earthquake was noticed. The greater distance at which the Charleston earthquake was felt, should probably be attributed to the greater elasticity of the rocks cut by the fault as well as to the higher intensity per unit area of fault-plane. The rocks cut by the San Andreas fault are for the most part sedimentary in origin and Mesozoic or later in age; the rocks underlying the Coastal Plain formations of South Carolina are highly crystalline igneous and metamorphic rocks, chiefly pre-Cambrian in age.

Great tectonic earthquakes are usually followed by numerous

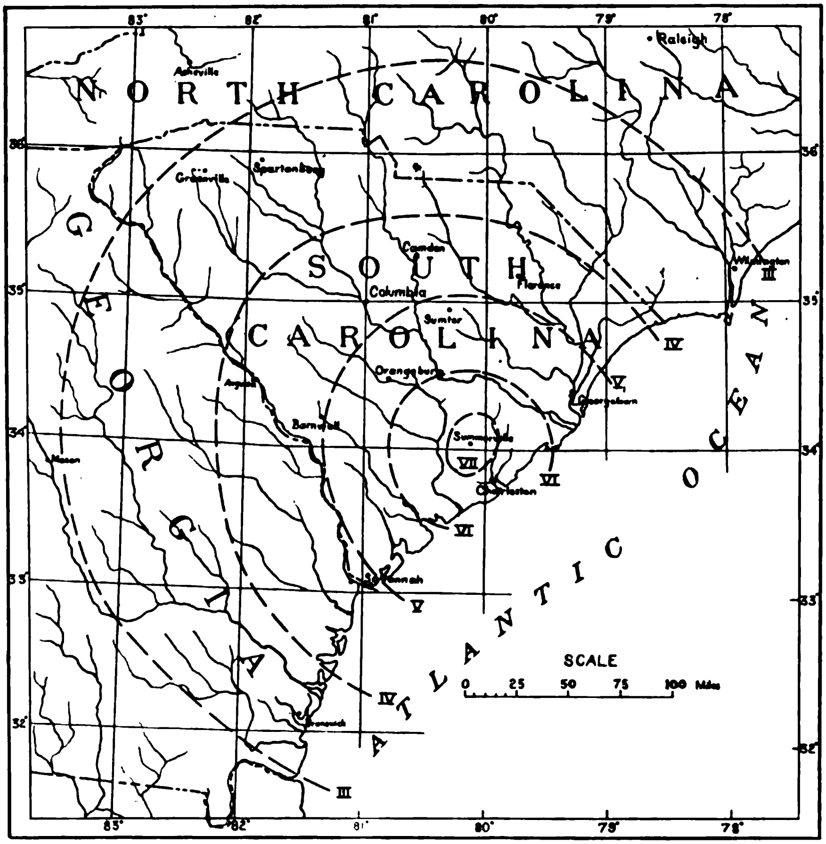

Fig. 3.—Isoseismals of the South Carolina Earthquake of June 12, 1912. Rossi-Forel scale.

aftershocks, and the frequency of their occurrence after the Charleston earthquake has been commented on elsewhere in this paper. Near Summerville the shocks were felt every few minutes for several days after the principal disturbance.

An important characteristic of the shocks occurring in this area is the noise accompanying them. Although a roaring sound commonly accompanies earthquakes having an intensity above V in the Rossi-Forel scale, the sounds heard near Summerville appear to be exceptional, for they are not only unusually loud, but are sometimes heard when the shocks themselves are so slight that they would otherwise pass unnoticed. Dutton, in writing of the minor shocks that followed the principal disturbance of August 31, 1886, states: "Almost all of them were accompanied by loud detonations. . . . . They were heard throughout the entire epicentral tract, though it is difficult [because of the sparse population] to determine whether they were as loud and frequent in other parts of that tract as at Summerville. . . . But the testimony is clear that at Summerville the sounds were very loud and of an explosive character."[41] This was also an important characteristic of the shocks that preceded the principal disturbance. The first of the preliminary shocks on the morning of August 27th was similar to an explosion. "Some thought a heavy cannon or blast of gunpowder had been fired. Others imagined the explosion of a locomotive or the boiler of some of the phosphate works on the banks of the neighboring rivers. The sound and the shock were sudden and simultaneous, conveying to everyone an idea of nearness of the originating cause."[42]

The explanation of all these peculiarities is probably to be found in the geologic structure; the disturbances originate in the highly elastic rocks of the crystalline basement, but reach the surface only after passing through the thick blanket of sedimentary materials, saturated with water. There is indeed a certain resemblance between the descriptions of the feebler shocks and sounds occurring near Summerville and the descriptions of earthquakes felt aboard vessels at sea.

CONCLUSIONS

The detailed investigations described in this paper lead to the following conclusions:

1. The South Carolina Coastal Plain has been a region of relatively low seismic activity since Cretaceous times.

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[41] Ibid., pp. 276-277.

[42] Ibid., p. 270.

2. The seismicity of the area has been decreasing gradually though irregularly since 1886.

3. Most of the earthquakes are probably due to adjustments taking place along a fault in the crystalline rocks underlying the Coastal Plain formations, the fault being located in the vicinity of Woodstock and extending in a northeast and southwest direction. Slow crustal movements cause strains which gradually accumulate until the resulting stresses are sufficient to produce dislocation. Many of the shocks are to be attributed to the adjustment of minor stresses set up by the more important movements. No great amount of displacement has probably resulted from any or all of the recent disturbances.

4. There is a limit to the amount of displacement which may occur along a given fault-plane at one time, and the limiting factors are: (1) the elastic limit and coefficient of elasticity of the rocks involved; (2) the stress necessary to cause rupture; and (3) the distance from the fault-plane to a region of no distortion.

5. The increase or decrease of pressure, when uniformly distributed over the surface on both sides of the fault, does not noticeably affect the earthquake frequency.

6. Any factor increasing the relative pressure on the northwest side of the assumed fault or decreasing it on the southeast side tends to increase the slowly accumulating stresses that result in readjustments with their accompanying earthquake shocks. While such factors may control the time of seismic disturbances they are not to be regarded as causes.

7. The most important factors affecting the relative pressure on opposite sides of the fault and thus controlling the earthquake frequency are rainfall, height of the water-table and barometric pressure.

8. Changes in the relative height of sea level result in very little effect on the earthquake frequency, probably because of the distance of the fault from the shore line.

9. There is no apparent relation between earthquake frequency in this district and sun-spot frequency or lunar periodicities.

10. In this district earthquakes are most common in September and least likely to occur in April.

11. The peculiarities which characterize the earthquakes of this district are probably due to the geologic structure.

LIST OF EARTHQUAKE SHOCKS ORIGINATING IN THE ATLANTIC COASTAL PLAIN REGION NEAR CHARLESTON, S. C.

The information given in this table was compiled from many sources and acknowledgment is made on page 118 of this paper for the principal lists that were used. The authority for each shock listed is shown by the initials given in the last column of the table. Whenever the information at hand was sufficient, the intensity of the shocks has been estimated in terms of the Rossi-Forel scale. In many cases, however, the observer has merely described the shock as slight, severe or strong, and when this has been done the adjective used is given in the column headed "Intensity." In a few instances the exact time or the exact day of the month was not known, but all of the occurrences listed are believed to be accurate within reasonable limits.

ABBREVIATIONS USED

C. E. D.—C. E. Dutton.
C. G. R.—C. G. Rockwood, Jr.
C. W. B.—U. S. Weather Bureau Station at Charleston, S. C.
E. H. G.—Miss E. H. Gadsden.
G. E. M.—G. E. Manigault.
H. F. R.—Harry Fielding Reid.
J. K.—James Kershaw.
L. R. G.—L. R. Gibbes.
N. & C.—*News and Courier,* Charleston, S. C.
T. C. M.—T. C. Mendenhall.
W. A. C.—William A. Courtenay.
W. L. K.—William L. King.
W. M. T.—W. M. Thomas.

LIST OF EARTHQUAKE SHOCKS ORIGINATING IN THE ATLANTIC COASTAL PLAIN REGION NEAR CHARLESTON, S. C.

Date	Time	Intensity	Remarks	Authority
1754 May 19	....	Slight	Recorded at Charleston.	W. A. C.
1799 Apr. 4	....	Strong	Accompanied by a rumbling sound. Recorded at Charleston.	W. A. C.
Apr. 11	3:20 a.m.	Strong	Recorded at Camden. Noise like thunder.	J. K.
Apr. 11	4:55 p.m.		Recorded at Camden.	J. K.
1843 Feb. 7	10:00 a.m.	Slight	Two shocks accompanied by rumbling sound. Recorded at Charleston.	W. L. K. and W. A. C.
1857 Dec. 19	9:04 a.m.		Horizontal oscillations accompanied by rumbling noise lasting 6 or 8 seconds.	L. R. G. and W. A. C.
1860 Oct. ..	....	Slight	Recorded at Charleston.	L. R. G.
1876 Dec. 12	Evening	Slight	Recorded at Charleston.	C. G. R.
1886 June ..	....	Slight	Slight tremors accompanied by noise. Observed at Charleston.	L. R. G.
Aug. 27	1:30 a.m.	Slight	Observed at Summerville by Mr. E. J. Tighe.	W. A. C.
Aug. 27	8:30 a.m.	V?	Observed at Summerville.	W. A. C. and others.
Aug. 28	5:30 a.m.		Felt at Summerville and by a few people in Charleston.	W. M. T. and others.
Aug. 29	....		Light tremors with some sound at Summerville.	W. M. T. and others.
Aug. 31	9:51 p.m.	X	Very destructive. Accompanied by a loud roaring noise. Dr. G. E. Manigault on page 241 of the Ninth Ann. Rept. U. S. Geol. Survey lists 8 shocks as occurring on Aug. 31, 1886.	C. E. D. and others.
Aug. 31	9:59 p.m.			N. and C.
Aug. 31	10:09 p.m.			N. and C.
Aug. 31	10:14 p.m.		Felt in Charleston.	N. and C.
Aug. 31	10:30 p.m.		Felt in Charleston.	N. and C.
Sept. 1	12:55 a.m.		Felt in Charleston.	N. and C.
Sept. 1	1:05 a.m.	Severe	Felt in Charleston.	N. and C. and T. C. M.
Sept. 1	2:00 a.m.		Felt in Charleston.	N. and C.
Sept. 1	4:00 a.m.		Felt in Charleston.	N. and C.
Sept. 1	8:25 a.m.		Felt in Charleston.	T. C. M.
Sept. 1	9:00 a.m.		Felt in Charleston.	N. and C.
Sept. 1	9:59 a.m.		Felt in Charleston.	T. C. M.
Sept. 1	1:00 p.m.		Felt in Charleston.	N. and C.
Sept. 1	5:15 p.m.		Felt in Charleston.	N. and C. and T .C. M.
Sept. 1	5:52 p.m.	Very slight	Felt in Charleston.	T. C. M.
Sept. 1	8:00 p.m.	Very slight	Felt in Charleston.	N. and C.
Sept. 1	11:55 p.m.	V?	Felt in Charleston.	N. and C. and T. C. M.
Sept. 2	11:53 p.m.		Felt in Charleston. Dr. Manigault lists 3 shocks for this day.	T. C. M.
Sept. 3	11:01 p.m.	VI	Dr. Manigault lists 2 shocks on this day	T. C. M.
Sept. 4	8:37 p.m.		Dr. Manigault lists 2 shocks on this day.	N. and C.

Date	Time	Intensity	Remarks	Authority
Sept. 5	11:06 p.m.	VI	Felt in Charleston and Summerville.	N. and C. and T. C. M.
Sept. 5	11:15 p.m.		Felt in Charleston.	N. and C.
Sept. 6	7:30 a.m.	Slight	Recorded in Summerville.	N. and C.
Sept. 6	11:35 a.m.	Very perceptible	Recorded in Summerville.	N. and C.
Sept. 6	1:40 p.m.		Recorded in Summerville.	N. and C.
Sept. 7	7:00 a.m.		Recorded in Summerville.	N. and C.
Sept. 7	9:00 a.m.		Recorded in Summerville.	N. and C.
Sept. 7	11:30 a.m.		Recorded in Summerville.	N. and C.
Sept. 7	4:52 p.m.		Recorded in Summerville.	T. C. M.
Sept. 7	5:00 p.m.		Recorded in Summerville.	N. and C.
Sept. 8	12:55 p.m.		Recorded at Charleston and Summerville.	N. and C. and T. C. M.
Sept. 9	1:06 a.m.		Recorded at Charleston. Accompanied by heavy rumbling.	T. C. M.
Sept. 10	....		Reported at Charleston.	G. E. M.
Sept. 12	....		Recorded at Charleston.	G. E. M.
Sept. 13	9:00 a.m.	Slight	Recorded at Summerville.	N. and C.
Sept. 14	....	Slight	Several shocks recorded at Summerville this day.	N. and C.
Sept. 15	....		Recorded at Charleston.	G. E. M.
Sept. 15	....		Recorded at Charleston.	G. E. M.
Sept. 21	4:25 a.m.	Slight	Recorded at Oakley.	N. and C.
Sept. 21	5:15 a.m.	Severe	Recorded in Charleston and elsewhere.	W. A. C.
Sept. 21	5:30 a.m.	V-VI	Recorded at Summerville.	N. and C.
Sept. 21	4:15 p.m.	Slight	Recorded at Oakley.	N. and C.
Sept. 22	....		Recorded at Charleston.	G. E. M.
Sept. 27	2:02 p.m.	VI	Recorded in Charleston.	T. C. M.
Sept. 27	5:02 p.m.	V?	Recorded in Charleston, Orangeburg, Kingsville, Camden and Savannah.	N. and C. and W. A. C.
Sept. 28	1:00 p.m.	Slight	Recorded in Charleston. Three shocks recorded this day at Summerville.	N. and C. and T. C. M.
Sept. 30	2:20 p.m.	Slight	Recorded at Summerville.	N. and C.
Sept. 30	5:10 p.m.	Slight	Recorded at Summerville.	N. and C.
Oct. 8	10:40 p.m.	Very perceptible	Recorded at Summerville.	N. and C.
Oct. 9	12:40 a.m	Very perceptible	Recorded at Summerville.	N. and C.
Oct. 9	1:48 a.m	VI?	Recorded at Summerville, Augusta and elsewhere.	N. and C.
Oct. 9	1:46 p.m.		Undulations with rumbling lasting 5 seconds.	C. W. B.
Oct. 15	4:00 a.m.	Slight	Recorded at Charleston.	C. W. B.
Oct. 15	7:40 a.m.	Slight	Recorded at Charleston.	C. W. B.
Oct. 22	5:20 a.m.	VII	Recorded in Charleston, Atlanta, Augusta and elsewhere.	W. A. C. and C. W. B.
Oct. 22	2:45 p.m.	VIII	Recorded at Summerville, Washington, Richmond, Louisville and elsewhere.	W. A. C. and C. W. B.
Oct. 22	8:07 p.m.	Marked	Recorded at Charleston.	C. W. B.
Oct. 22	11:54 p.m.	Slight	Recorded in Charleston. Accompanied by report like distant cannon.	W. A. C.
Oct. 30	3:40 a.m.	Slight	Recorded in Charleston.	C. W. B.
Oct. 31	2:21 p.m.	Slight	Recorded at Summerville and Charleston.	N. and C. and C. W. B.
Oct. 31	4:46 p.m.	Slight	Recorded at Summerville.	N. and C.
Nov. 5	12:20 p.m.	VIII	Recorded at Charleston, Richmond, Washington and elsewhere.	W. A. C. and C. W. B.

Date	Time	Intensity	Remarks	Authority
Nov. 7	2:00 p.m.	Slight	Recorded at Charleston.	C. W. B.
Nov. 17	....		Recorded at Summerville.	N. and C.
Nov. 28	10:10 a.m	Slight	Recorded at Summerville.	N. and C.
Nov. 28	3:30 p.m.	Sharp	Recorded at Charleston and Summerville. Preceded by roaring sound.	N. and C. and C. W. B.
Dec. 1	....		Three slight shocks recorded at Summerville this day.	N. and C.
Dec. 2	1:36 a.m.	Slight	Recorded in Charleston.	N. and C.
Dec. 2	8:00 a.m.	Slight	Recorded in Charleston. Accompanied by much noise.	C. W. B. and N. and C.
Dec. 6	....	Slight	Recorded in Charleston.	C. W. B.
1887				
Jan. 3	1:20 a.m.	Slight	Recorded in Charleston.	C. W. B.
Jan. 4	6:44 a.m.	VI	Recorded in Charleston, Columbia, Augusta and Savannah.	C. W. B. and N. and C.
Jan. 4	7:40 a.m.		Recorded in Charleston.	N. and C.
Jan. 10	7:57 p.m.	Slight	Recorded at Charleston.	C. W. B.
Feb. 26	6:00 a.m.	Slight	With rumbling. Recorded at Charleston.	C. W. B.
Mch. 4	2:00 a.m.	Slight	Recorded at Charleston.	C. W. B.
Mch. 17	9:09 a.m.	Slight	Recorded at Charleston.	C. W. B.
Mch. 18	6:10 p.m.	Slight	Recorded at Charleston.	C. W. B. and N. and C.
Apr. 9	7:00 a.m.	Slight	Recorded at Charleston.	W. A. C.
Apr. 10	6:30 a.m.	Slight	Recorded at Charleston.	C. W. B.
Apr. 14	7:00 a.m.	Slight	Recorded at Charleston.	W. A. C.
May 11	10:30 p.m.	Slight	Recorded at Charleston.	W. A. C.
May 12	12:+ a.m	Slight	Recorded at Charleston.	W. A. C.
June 3	7:00 a.m.	IV	Recorded at Charleston and Columbia.	W. A. C.
June 5	7:00 p.m.	II	Recorded at Charleston.	W. A. C.
June 5	....		Several tremors recorded this day at Pineopolis.	N. and C.
July 10	1:00 p.m.	Decided	Recorded in Charleston.	C. W. B.
1888				
Jan. 12	9:50 a.m.	Slight	Recorded in Charleston.	C. W. B.
Jan. 12	10:54 a.m.	VII	Recorded in Charleston.	L. R. G.
Jan. 15	6:40 p.m.	Slight	Recorded in Charleston.	C. W. B.
1891				
Oct. 13	12:55 a.m.	Decided	Recorded in Charleston. Vibrations accompanied by rumbling.	C. W. B.
Dec. 5	5:10 p.m.		Recorded in Charleston. Bouncing vertical movement.	C. W. B.
1892				
Nov. 3	12:25 p.m.	Slight	Recorded in Charleston. Tremors.	C. W. B.
Nov. 3	11:45 p.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 4	3:09 a.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 4	6:20 a.m.		Recorded in Charleston. Light thumps.	C. W. B.
Nov. 6	2:53 a.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 8	3:03 a.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 8	7:25 a.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 9	4:20 p.m.		Recorded in Charleston. Light thumps.	C. W. B.
Nov. 9	11:02 p.m.		Recorded in Charleston. Tremors and light thumps.	C. W. B.
Nov. 10	6:58 a.m.		Recorded in Charleston. Tremors.	C. W. B.
Nov. 10	5:03 p.m.		Recorded in Charleston. Light tremors and thumps.	C. W. B.
Nov. 10	11:47 p.m.		Recorded in Charleston. Rumbling and light thumps.	C. W. B.
Nov. 11	12:34 a.m.		Recorded in Charleston. Light tremors.	C. W. B.

Date	Time	Intensity	Remarks	Authority
Nov. 11	2:47 a.m.		Recorded in Charleston. Light tremors.	C. W. B.
Nov. 11	11:02 p.m.		Recorded in Charleston. Light thumps.	C. W. B.
Nov. 23	1:20 a.m.		Recorded in Charleston. Light tremors.	C. W. B.
Dec. 22	2:05 a.m.		Recorded in Charleston. Light thump.	C. W. B.
Dec. 22	6:02 a.m.		Recorded in Charleston. Light tremors.	C. W. B.
1893				
Feb. 13	7:17 p.m.		Recorded in Charleston. Light thumps.	C. W. B.
Feb. 14	1:14 a.m.		Recorded in Charleston. Light tremor.	C. W. B.
Mch. 2	4:03 a.m.		Recorded in Charleston. Light tremors and thumps.	C. W. B.
Mch. 2	11:04 a.m.		Recorded in Charleston. Light tremors.	C. W. B.
Mch. 3	5:30 a.m.		Recorded in Charleston. Light tremors.	C. W. B.
Mch. 3	6:27 a.m.		Recorded in Charleston. Light thumps.	C. W. B.
Mch. 7	10:57 p.m.		Recorded at Charleston. Light waves and thumps.	C. W. B.
June 20	11:05 p.m.	Strong	Recorded at Charleston. Tremors and waves with roaring noise. Locally considered heaviest since 1886.	C. W. B.
June 21	4:12 a.m.		Recorded at Charleston. Slight tremors and rocking motion.	C. W. B.
June 21	4:48 a.m.		Recorded at Charleston. Slight tremors and rocking motion.	C. W. B.
June 23	7:22 p.m.		Recorded at Charleston. Slight tremors and rocking motion.	C. W. B.
June 24	1:35 a.m.		Recorded at Charleston. Tremors lasting 5 seconds.	C. W. B.
June 27	9:31 a.m.		Recorded at Charleston. Tremors lasting 4 seconds.	C. W. B.
June 29	12:24 a.m.		Recorded at Charleston. Light waves and tremors lasting 3 seconds.	C. W. B.
July 3	11:55 a.m.		Recorded at Charleston. Light waves and tremors lasting 3 seconds.	C. W. B.
July 3	2:50 p.m.		Recorded at Charleston. Light waves and tremors lasting 5 seconds.	C. W. B.
July 3	9:50 p.m.		Recorded at Charleston. Light waves and tremors lasting 3 seconds.	C. W. B.
July 4	3:45 a.m.		Recorded at Charleston. Light waves and tremors lasting 2 or 3 seconds.	C. W. B.
July 4	11:20 p.m.		Recorded at Charleston. Light waves and tremors lasting 8 seconds.	C. W. B.
July 5	3:10 a.m.		Recorded at Charleston. One decided thump and tremors lasting 6 seconds.	C. W. B.
July 5	10:20 p.m.		Recorded at Charleston. Tremors lasting 5 seconds.	C. W. B.
July 6	12:25 a.m.		Recorded at Charleston. Light tremors and waves lasting 7 seconds.	C. W. B.
July 6	4:05 a.m.	Decided	Recorded at Charleston. Moderate waves lasting 7 seconds.	C. W. B.
July 7	7:15 a.m.		Recorded at Charleston. Light waves and tremors lasting 3 seconds.	C. W. B.
July 7	11:50 p.m.		Recorded at Charleston. Light waves and tremors lasting 10 seconds.	C. W. B.
July 8	2:18 a.m.		Recorded at Charleston. Light tremors and moderate wave lasting 5 seconds.	C. W. B.
July 8	10:25 a.m.		Recorded at Charleston. Moderate wave and light tremors lasting 15 to 20 seconds.	C. W. B.

Date	Time	Intensity	Remarks	Authority
July 8	10:59 a.m.		Recorded at Charleston. Light tremors.	C. W. B.
July 9	12:10 a.m.		Recorded at Charleston. Light tremors and waves continuing until 5:30 a.m.	C. W. B.
July 9	3:00 a.m.		Recorded at Charleston. Light trembling.	C. W. B.
July 10	10:12 p.m.		Recorded at Charleston. Wave and light tremors lasting 15 seconds.	C. W. B.
July 11	9:10 p.m.		Recorded at Charleston. Tremors at intervals until 10:45 p.m.	C. W. B.
July 22	11:15 p.m.		Recorded at Charleston. Light tremors.	C. W. B.
July 25	2:54 a.m.		Recorded at Charleston. Light tremors.	C. W. B.
Aug. 2	9:05 p.m.		Recorded at Charleston. Light tremors and wave lasting 7 seconds.	C. W. B.
Aug. 9	11:00 p.m.		Recorded at Charleston. Light wave and tremors at intervals until 11:32 p.m.	C. W. B.
Aug. 13	11:10 p.m.		Recorded at Charleston. Single light wave.	C. W. B.
Aug. 17	1:25 a.m.		Recorded at Charleston. A few light tremors.	C. W. B.
Sept. 6	12:10 a.m.		Recorded at Charleston. Light tremors lasting 8 seconds.	C. W. B.
Sept. 19	12:25 a.m.		Recorded at Charleston. Light waves, light tremors, light thumps and light roars continuing until 5:10 a.m. Most marked at 2:05 a.m., 2:40 a.m. and 3:55 a.m.	C. W. B.
Sept. 21	12:40 a.m.		Recorded at Charleston. Light thumps, roars, tremors and waves lasting 4 to 8 seconds.	C. W. B.
Sept. 21	2:25 a.m.		Recorded at Charleston. Light thumps. roars, tremors and waves lasting 4 to 8 seconds.	C. W. B.
Sept. 21	8:40 p.m.		Recorded at Charleston. Light waves and tremors at intervals until 10:20 p.m.	C. W. B.
Sept. 24	10:20 p.m.		Recorded at Charleston. Light waves and tremors lasting 6 seconds.	C. W. B.
Sept. 24	11:25 p.m.		Recorded at Charleston. Light waves and tremors lasting 6 seconds.	C. W. B.
Sept. 25	4:30 a.m.		Recorded at Charleston. Light waves and tremors lasting 8 seconds.	C W. B.
Sept. 26	8:25 p.m.		Recorded at Charleston. Light tremors and waves lasting 8 seconds.	C. W. B.
Sept. 29	9:10 p.m.		Recorded at Charleston. Tremors and waves lasting 8 seconds.	C. W. B.
Sept. 30	4:05 a.m.		Recorded at Charleston. Tremors, waves and roars lasting until 4:12 a.m. Light tremors during entire morning.	C. W. B.
Sept. 30	8:50 p.m.		Recorded at Charleston. Waves and thumps lasting 3 seconds.	C. W. B.
Oct. 1	8:58 p.m.		Recorded at Charleston. Light tremors.	C. W. B.
Oct. 1	10:15 p.m.		Recorded at Charleston. Light tremors.	C. W. B.
Oct. 1	10:35 p.m.		Recorded at Charleston. Light tremors.	C. W. B.
Oct. 7	11:28 p.m.		Recorded at Charleston. Light waves lasting 8 seconds.	C. W. B.

Date	Time	Intensity	Remarks	Authority
Oct. 9	9:35 p.m.		Recorded at Charleston. Light waves, light tremors and a few light rumblings at short intervals until 11:50 p.m. All pass from NW. to SE.	C. W. B.
Oct. 16	8:40 p.m.		Recorded at Charleston. Light tremors and waves lasting 20 seconds.	C. W. B.
Oct. 23	10:20 p.m.		Recorded at Charleston.. Tremors continuing for some time.	C. W. B.
Oct. 25	....		Recorded at Charleston. Light tremors throughout the early morning.	C. W. B.
Nov. 7	11:40 p.m.		Recorded at Charleston. Marked thumps, waves and tremors lasting 5 minutes.	C. W. B.
Nov. 8	1:05 a.m.		Recorded at Charleston. Swaying tremors, waves and thumps lasting 11 sec.	C. W. B.
Dec. 3	11:35 a.m.		Recorded at Charleston. Heavy thumps lasting 2 seconds.	C. W. B.
Dec. 27	1:51 a.m.		Recorded at Charleston. Rocking, swaying tremors with light rumbling lasting 2 to 4 seconds.	C. W. B.
Dec. 27	2:17 a.m.		Recorded at Charleston. Rocking, swaying tremors with light rumbling lasting 2 to 4 seconds.	C. W. B.
Dec. 27	4:09 a.m.		Recorded at Charleston. Rocking, swaying tremors with light rumbling lasting 2 to 4 seconds.	C. W. B.
Dec. 27	4:56 a.m.		Recorded at Charleston. Rocking, swaying tremors with light rumbling lasting 2 to 4 seconds.	C. W. B.
Dec. 27	9:20 p.m.	Decided	Recorded at Charleston. Decided shock with light waves, tremors, and roars lasting 5 seconds.	C. W. B.
Dec. 28	10:46 p.m		Recorded at Charleston. Tremors and rumbling lasting 7 seconds.	C. W. B.
" 29-30	....		Recorded at Charleston. Tremors at intervals through the night and probably continuing through the day, but difficult of observation because of street traffic.	C. W. B.
" 30-31	....		Recorded at Charleston. Tremors and waves at slight intervals through the night.	C. W. B.
1894				
Jan. 10	....		Recorded at Charleston. Tremors at intervals during early morning. Most marked at 3:05 a.m., 3:49 a.m. and 4:15 a.m.	C. W. B.
Jan. 18	1:45 a.m.		Recorded at Charleston. Distinct tremors and rocking motion. Light tremors were felt nearly all of the morning until 6 a.m.	C. W. B.
Jan. 29	11:05 p.m.	Decided	Recorded at Charleston. Decided shock. Duration 2 seconds.	C. W. B.
Feb. 1	12:21 a.m	Decided	Recorded at Charleston. Tremors and rocking motion continuing at intervals until daybreak.	C. W. B.

Date	Time	Intensity	Remarks	Authority
Feb. 14	12:40 a.m.		Recorded at Charleston. Tremors and vibrations at intervals until 3:50 a.m.	C. W. B.
Mch. 4	11:15 p.m.		Recorded at Charleston. Light tremors.	C. W. B.
Mch. 13	10:25 p.m.		Recorded at Charleston. Light tremors and a thump.	C. W. B.
Mch. 16	2:50 p.m.		Recorded at Charleston. Rockings, tremors and rumblings lasting 8 sec.	C. W. B.
Apr. 15	3:20 a.m.		Recorded at Charleston. Light tremors lasting 8 seconds.	C. W. B.
May 26	3:15 a.m.		Recorded at Charleston. Light tremors.	C. W. B.
June 6	6:05 a.m.		Recorded at Charleston. Tremors and swaying motion lasting until 6:12 a.m.	C. W. B.
June 9	5:55 a.m.		Recorded at Charleston. Tremors, waves and slight roar lasting 6 to 10 seconds.	C. W. B.
June 15	8:52 p.m.		Recorded at Charleston. Tremors at intervals for several hours.	C. W. B.
June 15	9:16 p.m.	Decided	Recorded at Charleston.	C. W. B.
Aug. 11	12:10 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 15 seconds.	C. W. B.
Aug. 11	12:20 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 10 seconds.	C. W. B.
Aug. 13	10:45 p.m.		Recorded at Charleston. Light tremors and vibrations lasting 5 seconds.	C. W. B.
Aug. 16	12:06 a.m.		Recorded at Charleston. Light tremors lasting 8 seconds.	C. W. B.
Aug. 18	11:23 p.m.		Recorded at Charleston. Tremors and gentle swaying lasting until 11:28 p.m.	C. W. B.
Aug. 18	11:46 p.m.		Recorded at Charleston. Tremors and gentle swaying lasting until 11:48 p.m.	C. W. B.
Aug. 20	2:40 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 6 seconds.	C. W. B.
Sept. 6	11:05 p.m.		Recorded at Charleston. Light tremors lasting 25 seconds.	C. W. B.
Sept. 10	2:33 a.m.		Recorded at Charleston. Light tremors lasting until 2:46 a.m.	C. W. B.
Sept. 12	12:10 a.m.		Recorded at Charleston. Light tremors lasting 15 seconds.	C. W. B.
Sept. 12	12:25 a.m.		Recorded at Charleston. Light tremors lasting 15 seconds.	C. W. B.
Oct. 27	2:10 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 5 seconds.	C. W. B.
Dec. 11	12:27 a.m.		Recorded at Charleston. Light tremors and rocking lasting 5 seconds.	C. W. B.
Dec. 20	4:40 a.m.		Recorded at Charleston. Tremors.	C. W. B.
Dec. 20	5:50 a.m.		Recorded at Charleston. Tremors.	C. W. B.
Dec. 29	2:59 a.m.		Recorded at Charleston. Tremors and vibrations lasting 15 seconds.	C. W. B.
1895				
Jan. 8	12:40 a.m.		Recorded at Charleston. Tremors, rocking and swaying with roars, continuing at intervals until 5:00 a.m. Quite marked at 12:58 a.m. and 2:29 a.m.	C. W. B.
Jan. 10	3:08 a.m.		Recorded at Charleston. Light tremors and rumblings lasting 12 seconds.	C. W. B.
Feb. 7	7:53 a.m.		Recorded at Charleston. Tremors, vibrations and roars lasting 5 seconds.	C. W. B.

Date	Time	Intensity	Remarks	Authority
Apr. 27	2:40 a.m.		Recorded at Charleston. Rocking, swaying, light tremors and slight rumbling lasting 10 seconds.	C. W. B.
May 6	3:50 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 10 seconds.	C. W. B.
July 25	12:46 a.m.		Recorded at Charleston. Light tremors lasting 10 seconds.	C. W. B.
July 25	1:08 a.m.		Recorded at Charleston. Light tremors lasting 10 seconds.	C. W. B.
Oct. 6	1:25 a.m.		Recorded at Charleston. Light tremors and slight swaying motion with one decided thump. Duration 11 seconds.	C. W. B.
Oct. 20	12:08 p.m.		Recorded at Charleston. Swaying and rocking. Duration 3 seconds.	C. W. B.
Oct. 31	6:14 a.m.		Recorded at Charleston. Light tremors and vibrations lasting 8 seconds.	C. W. B.
Nov. 6	12:10 a.m.		Recorded at Charleston. Vertical tremors lasting 3 minutes, 30 seconds.	C. W. B.
Nov. 12	6:33 p.m.		Recorded at Charleston. Rocking and swaying motion lasting 4 seconds.	C. W. B.
Nov. 12	10:11 p.m.		Recorded at Charleston. Three moderate vibrations lasting 2 seconds.	C. W. B.
Dec. 3	12:26 a m.		Recorded at Charleston. Tremors at rate of about 5 per second for 20 seconds.	C. W. B.
Dec. 26	1:46 a.m.		Recorded at Charleston. Vertical vibrations lasting 3 minutes.	C. W. B.
1896				
Feb. 9	11:18 p.m.		Recorded at Charleston. Light tremors lasting 15 seconds.	C. W. B.
Mch. 1	2:50 a.m.		Recorded at Charleston. Tremors and vibrations continuing until 3:20 a.m.	C. W. B.
Mch. 2	8:45 p.m		Recorded at Charleston. Light tremors continuing until 2:40 a.m. of March 3.	C. W. B.
Mch. 19	3:22 a.m		Recorded at Charleston. Decided vibrations lasting 3 seconds.	C. W. B.
May 21	1:05 a.m		Recorded at Charleston. Light tremors continuing until 4:30 a.m.	C. W. B.
May 31	3:09 a.m.		Recorded at Charleston. Tremors continuing until 3:46 a.m.	C. W. B.
June 1	4:51 a.m.		Recorded at Charleston. Light tremors continuing until 5:30 a.m.	C. W. B.
June 23	12:51 a.m.		Recorded at Charleston. Light tremors continuing until 5:10 a.m.	C. W. B.
June 29	1:49 a.m.		Recorded at Charleston. Tremors and swaying motion continuing until 5:20 a.m.	C. W. B.
June 30	12:12 a.m.		Recorded at Charleston. Tremors and swaying motion continuing until 3:59 a.m.	C. W. B.
Aug. 7	12:56 a.m.		Recorded at Charleston. Light tremors of short duration.	C. W. B.
Aug. 7	2:45 a.m.		Recorded at Charleston. Light tremors of short duration.	C. W. B.
Aug. 7	4:02 a.m		Recorded at Charleston. Light tremors of short duration.	C. W. B.

Date	Time	Intensity	Remarks	Authority
Aug. 11	12:58 a.m.		Recorded at Charleston. Tremors and swaying motion continuing until 4:35 a.m. Decided shocks at 12:58 a.m., 1:14 a.m., 3:15 a.m. and 4:24 a.m.	C. W. B.
Aug. 12	2:42 a.m.		Recorded at Charleston. Tremors and swaying motion continuing until 3:36 a.m.	C. W. B.
Aug. 12	10:25 p.m.		Recorded at Charleston. Tremors continuing until 3:20 a.m. Aug. 13.	C. W. B.
Aug. 14	12:43 a.m.		Recorded at Charleston. Tremors and swaying motion continuing until 4:25 a.m.	C. W. B.
Aug. 15	3:16 a.m.		Recorded at Charleston. Light tremors and swaying motion.	C. W. B.
Aug. 16	3:20 a.m.		Recorded at Charleston. Light tremors and swaying motion.	C. W. B.
Aug. 17	12:45 a.m.		Recorded at Charleston. Tremors and slight swaying motion continuing until 4:10 a.m.	C. W. B.
Aug. 29	10:24 p.m.		Recorded at Charleston. Light tremors and rocking motion lasting until 10:39 p.m.	C. W. B.
Sept. 8	8:31 a.m.		Recorded at Charleston. Tremors.	C. W. B.
Sept. 8	1:16 p.m.		Recorded at Charleston. Decided thump. vibrations and swaying.	C. W. B.
Sept. 10	9:50 p.m.		Recorded at Charleston. Light tremors continuing until 11:26 p.m.	C. W. B.
Sept. 11	12:11 a.m.		Recorded at Charleston. Light tremors continuing until 2:35 a.m.	C. W. B.
Sept. 13	12:20 a.m.		Recorded at Charleston. Light tremors and slight swaying continuing until 2:40 a.m.	C. W. B.
Nov. 14	3:15 a.m.		Recorded at Charleston. Deep rumblings, sharp thud and rapid vibrations lasting 5 seconds.	C. W. B.
1897				
Feb. 1	7:05 a.m.		Recorded at Charleston. Light tremors.	C. W. B.
Mch. 16	10:48 p.m.		Recorded at Charleston. Tremors lasting 40 seconds.	C. W. B.
Mch. 30	12:20 a.m.		Recorded at Charleston. Tremors and thumps lasting until 2:50 a.m.	C. W. B.
June 1	12:25 a.m.		Recorded at Charleston. Slight tremors.	C. W. B.
July 10	7:45 a.m.		Recorded at Charleston. Slight vibrations lasting 4 seconds.	C. W. B.
1898				
Aug. 3	4:30 p.m.		Recorded at Summerville. Tremors.	E. H. G.
Sept. 23	9:15 a.m.		Recorded at Summerville. Tremors.	E. H. G.
1899				
Mch. 10	12:45 a.m.	Sharp	Recorded at Summerville.	E. H. G.
Mch. 16	8:45 a.m.	Slight	Recorded at Summerville.	E. H. G.
May 5	5:43 a.m.	Slight	Recorded at Summerville.	E. H. G.
May 18	4:30 a.m.	Very slight	Recorded at Summerville.	E. H. G.
Dec. 4	7:48 a.m.	Sharp	Recorded at Summerville.	E. H. G.
1900				
Jan. 14	5:00 a.m.	Slight tremor	Recorded at Summerville.	E. H. G.
May 10	6:20 p.m.	Tremor	Recorded at Summerville.	E. H. G.
Aug. 10	7:50 p.m.	Slight	Recorded at Summerville.	E. H. G.

Date	Time	Intensity	Remarks	Authority
Sept. 4	6:05 a.m.	Slight	Recorded at Summerville.	E. H. G.
Sept. 24	2:36 p.m.		Recorded at Summerville.	E. H. G.
1901				
Jan. ..	....	Slight	Recorded at Summerville. Time unknown.	E. H. G.
Sept. 5	1:38 a.m.		Recorded at Summerville.	E. H. G.
Sept. 14	8:26 a.m.		Recorded at Summerville.	E. H. G.
Sept. 16	12:06 p.m.		Recorded at Summerville.	E. H. G.
Sept. 17	8:35 a.m.		Recorded at Summerville.	E. H. G.
Sept. ..	....	Slight	Recorded at Summerville. Time unknown.	E. H. G.
Sept. 28	8:25 p.m.		Recorded at Summerville.	E. H. G.
Dec. 1	7:26 p.m	IV-V	Recorded at Charleston. Slight vibration.	C. W. B. and others.
Dec. 1	7:35 p.m.		Recorded at Summerville. Probably the same as the shock recorded in Charleston at 7:26 p.m.	E. H. G.
1902				
Jan. 22	10:11 a.m.		Recorded at Summerville.	E. H. G.
Feb. 4	11:45 p.m.		Recorded at Summerville.	E. H. G.
Mch. 17	8:45 p.m.		Recorded at Summerville.	E. H. G.
Mch. 26	4:20 a.m.		Recorded at Summerville.	E. H. G.
May 15	10:30 p.m.	Not heavy	Recorded at Summerville.	E. H. G.
May 24	9:05 a.m.	Heavy	Recorded at Summerville. Long continued.	E. H. G.
Sept. 28	3:04 p.m		Recorded at Summerville.	E. H. G.
Nov. 20	....		Recorded at Summerville. Just after dawn.	E. H. G.
1903				
Jan. 23	8:00 p.m.	IV	Recorded at Charleston. Roar followed by marked shock and 10 distinct vibrations lasting 6 seconds.	H. F. R. and C. W. B
Jan. 23	8:10 p.m.		Recorded at Summerville. Two distinct booms. Undoubtedly the same shock as that reported at Charleston.	E. H. G.
Jan. 29	7:15 a.m.	Slight	Recorded at Summerville.	E. H. G.
Jan. 31	5:54 a.m.		Recorded at Charleston. Light thump preceded and followed by light, rapid tremors with swaying and roaring lasting 8 seconds.	C. W. B.
Feb. 3	5:06 a.m.		Recorded at Charleston. Roar, swaying and rapid tremors lasting 6 to 8 seconds.	C. W. B.
May 9	5:49 a.m.	Slight	Recorded at Summerville.	E. H. G.
June 16	10:49 p.m.		Recorded at Summerville.	E. H. G.
Aug. 25	9:56 a.m.	Slight	Recorded at Summerville.	E. H. G.
Dec. 24	2:35 a.m.		Recorded at Summerville.	E. H. G.
1904				
Mch. 5	8:40 p.m		Recorded at Summerville.	E. H. G.
Mch. 16	Night		Recorded at Summerville.	E. H. G.
June 19	9:15 a.m.		Recorded at Summerville.	E. H. G.
June 22	6:00 p.m.		Recorded at Summerville.	E. H. G.
Sept. 5	9:53 a.m.	Slight	Recorded at Summerville.	E. H. G.
Sept. 10	9:27 a.m.		Recorded at Summerville.	E. H. G.
Oct. 1	3:45 a.m.		Recorded at Summerville.	E. H. G.
Nov. 15	11:47 a.m.		Recorded at Summerville.	E. H. G.
Dec. 6	5:48 p.m.		Recorded at Summerville.	E. H. G.

Date	Time	Intensity	Remarks	Authority
1905				
Mch. 5	9:15 a.m.	Slight	Recorded at Summerville.	E. H. G.
June 3	7:00 p.m.	Slight	Recorded at Summerville.	E. H. G.
July 23	2:15 a.m.		Recorded at Summerville.	E. H. G.
July 23	2:25 a.m.		Recorded at Summerville.	E. H. G.
Oct. 11	1:45 p.m.	Slight	Recorded at Summerville.	E. H. G.
Oct. 16	2:10 a.m.		Recorded at Summerville.	E. H. G.
Dec. 27	10:15 p.m.		Recorded at Summerville.	E. H. G.
1906				
Aug. 5	1:20 a.m.	Slight	Recorded at Summerville.	E. H. G.
1907				
Apr. 19	3:30 a.m	IV-V	Recorded at Summerville, Charleston, Augusta and elsewhere.	C. W. B., E. H. G., H. F. R. and others.
1908				
Jan. 15	2:00 p.m.	Slight	Recorded at Summerville.	E. H. G.
Jan. 15	2:01 p.m.		Recorded at Summerville.	E. H. G.
Mch. 3	4:06 p.m.		Recorded at Summerville.	E. H. G.
Mch. 7	1:50 a.m.		Recorded at Summerville.	E. H. G.
Oct. 25	11:10 p.m.	Slight	Recorded at Summerville.	E. H. G.
Dec. 28	6:24 a.m.		Recorded at Summerville.	E. H. G.
1909				
Feb. 25	11:00 p.m.	Slight	Recorded at Summerville.	E. H. G.
Aug. 21	8:36 a.m.	Slight	Recorded at Summerville.	E. H. G.
Dec. 14	6:00 p.m.	Slight	Recorded at Summerville.	E. H. G.
1910				
May 2	4:15 a.m.	Slight	Recorded at Summerville.	E. H. G.
Sept. 2	2:18 a.m.	Slight	Recorded at Summerville.	E. H. G.
Sept. 12	3:29 p.m.	Slight	Recorded at Summerville.	E. H. G.
1911				
Nov. 24	7:17 a.m.		Recorded at Summerville and Charleston.	E. H. G. and C. W. B.
1912				
Mch. 31	3:25 p.m.		Recorded at Charleston. Slight vibrations.	C. W. B.
June 12	5:30 a.m.	VII	Recorded at Summerville, Charleston, Columbia, Savannah, Augusta, Brunswick and elsewhere. Shook down chimneys at Summerville. For isoseismals see map, fig. 3.	E. H. G., C. W. B. and others.
June 29	....	Slight	Recorded at Summerville.	E. H. G.
Aug. 30	11:52 a.m.		Recorded at Summerville.	
Sept. 29	3:06 a.m.		Recorded at Summerville. Awakened many in Charleston.	E. H. G. and C. W. B
Nov. 17	7:30 a.m.	Hard	Recorded at Summerville.	E. H. G.
Nov. 25	10:32 p.m.		Recorded at Summerville.	E. H. G.
Dec. 15	11:54 a.m.		Recorded at Summerville.	E. H. G.
1913				
Jan. 25	7:37 p.m.		Recorded at Summerville.	E. H. G.
Feb. 5	4:06 p.m.		Recorded at Summerville.	E. H. G.
Mch. 9	11:30 a.m.		Recorded at Charleston. Slight vibrations.	C. W. B.
June 6	1:20 p.m.		Recorded at Summerville.	E. H. G.

University of South Carolina,
Columbia, South Carolina,
July, 1914.

SEISMOLOGICAL NOTES

In Sumatra.—On June 26, 1914, a violent earthquake almost entirely destroyed the town of Benkulen in southern Sumatra. The government buildings were seriously damaged and many people were killed or wounded.

Valdez, Alaska.—On July 20th a sharp earthquake preceded by several light shocks was felt at Valdez, Alaska. No serious damage is reported.

New Hebrides.—Notice received from Sydney, New South Wales, dated July 24th, says the island of Aoba of the New Hebrides group has suffered greatly of late from violent earthquakes. The exact dates are not given.

Como, Italy.—A strong shock was felt at Como on August 20th, severe enough to cause great alarm.

Lake Honda, September 4, 1914.—The Spring Valley Water Company reports a slight earthquake shock at Lake Honda, one of the distributing reservoirs in the city limits of San Francisco, California, at 12:56 a.m. of September 4th. The locality is called "Laguna Honda" on map 17 of the atlas of the State Earthquake Commission. The shock was preceded by a low rumbling sound.

Tacoma, Washington.—An earthquake was felt at Tacoma, Washington, at 1:40 a.m. on September 5th. The intensity was between III and IV, R.-F. scale.

Asia Minor, October 5 (?).—It is reported from Constantinople that a violent earthquake at Isbarta and at Buldur killed and injured more than two thousand people. The region affected is in the mountains of Lycian Taurus, about seventy miles north of the Gulf of Adalia.

San Francisco Bay Region, California.—On September 7, 1914, a light earthquake was felt in that part of California lying west of San Francisco Bay. Several reports have been received and these are summarized below:—

Los Gatos.—Mr. Irving H. Snyder: time 10:50 a.m. "Movement was slight, but quite perceptible to persons sitting. No noise seemed to accompany the movement." Mr. Snyder writes that he has a reliable report from Santa Cruz saying that the shock was felt there also.

Mt. Hamilton.—Felt by several persons; Miss A. M. Hobe has kindly sent the following report of the seismographic records: "The times of the earthquakes on September 7th were:—

"First.—Beginning 10 h 5 m 36 s. This one dies away almost completely, if not entirely, after 2 m 44 s. But there is a distinct jolt of 5 s duration, beginning at 10 h 9 m 1 s.

"Second.—Beginning at 10 h 35 m 36 s; duration 10 s. Not felt here; very slight.

"Third.—Beginning at 1 h 10 m 14 s; duration 1 m 6 s."

San Jose.—L. S. Kroeck: time 10:05 a.m. Feeble shock; some freely-swinging objects were put into motion; felt by persons in sitting position; long duration.

Santa Clara.—No direct report was received from Santa Clara University, but a newspaper account states that the earthquake was recorded by both the horizontal and vertical arms of the seismograph, and that a more feeble shock was recorded at 1:10 p.m. of the same day.

Santa Cruz.—See Los Gatos.

Sausalito.—T. H. Claussen and Mr. Hohl: time 10:07. It rattled the windows of the town hall in which the men were working.

Stanford University.—J. C. Branner: time 10:05 a.m.; duration about four seconds; intensity III, R-F scale.

S. D. Townley: time 10:5:27 a.m.; duration ten seconds; intensity II to III, R-F scale.

Caraveli, Peru.—A message from Lima, Peru, dated September 12, 1914, says a violent earthquake has destroyed the town of Caraveli. The precise date and details are not given. On the 14th it was reported that thirty-five shocks had been recorded at Caraveli, and that they continued up to that day.

Caraveli is a town in the department of Arequipa, two hundred kilometers northwest of Mollendo, and sixty kilometers from the coast.

Guayaquil, Equador.—An earthquake occurred at Guayaquil, Equador, the morning of September 25th. It was sufficiently violent to cause a great panic, though no serious damage is reported.

Martinique, October 3.—A strong earthquake was felt at Fort de France, Island of Martinique, at 1:18 p.m. on October 3d. No damage has been reported.

Dr. Henry J. Johnston-Lavis, F. G. S., professor of vulcanology and allied sciences at the University of Naples, was killed in a motor accident near Bourges, France, on September 10th. He was a native of Devonshire, England, where he was born July 19, 1856. He is well known for his studies of vulcanology and seismology of southern Italy, on which he published more than one hundred and fifty papers.

REVIEWS

BERICHT ÜBER DIE MIR ZUGEGANGENEN URTEILE DER FACHGENOSSEN, BETREFFEND DIE IN "ZEITUNG VULCANOLOGISCHER FORSCHUNG" VON MIR GEMACHTEN VORSCHLÄGE. By Wilhelm Branca. *Abhandlungen der Königl. Preuss. Akademie der Wissenschaften, Jahrgang 1914. Phys.-Math. Klasse. Nr. 2, 1-67.*

In 1913 the author submitted[1] the following proposals, relative to vulcanological research, to many of his colleagues in various parts of the world:

1. International cooperation of all vulcanologists and vulcanological societies.

2. Publication of an international annual report (Jahresbericht) of volcanic phenomena in several languages.

3. Publication of an international journal (Zeitschrift) of vulcanology in several languages.

4. Establishment of a vulcanological research institute in as many countries as possible, one part of each institute to be devoted to theoretical and experimental investigation, the other to the field study of volcanoes and the collection of the rocks, minerals, and gases from volcanoes.

5. (*a*) The request to the various governments that ship-captains of their war-vessels and merchant marine be prevailed upon to report all submarine volcanic phenomena and sea-quakes.

5. (*b*) A brief polyglot instruction on the nature of volcanic phenomena, as well as a list of questions to be answered. These are to be sent to the various governments with the request that instruction in the same be given in the naval schools.

6. That the list proposed by the author be supplemented.

To these proposals seventy-one replies were received (thirty-five from German investigators and thirty-six from non-Germans), and the paper is devoted principally to extracts from the replies and comments upon them.

These replies indicate that the time is ripe for international cooperation in the study of volcanoes, and a willingness to cooperate is unanimously expressed.

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[1] *Sitzungsberichte der Konigl. Preuss. Akademie der Wissenschaften,* 1913, **38**, 810-856.

The paper closes with an account of the work thus far accomplished in Berlin. Until a German vulcanological institute can be established, the Academy of Science in Berlin acts in that capacity. A "Zeitschrift für Vulkanologie" in four languages—German, French, English, and Spanish—is to be published by Bornträger of Berlin under the editorship of Dr. Bergeat of Königsberg, Prussia.

At page 16 of the paper it is noted that there are 27 active volcanoes and from 170 to 235 extinct ones in the German colonies, so that the establishment of a German vulcanological institute seems to be entirely warranted.

A. F. ROGERS.

COME DOBBIAMO DIFENDERCI DAI TERREMOTI? By G. Agamennone. *Revista di Astronomia e Scienze affini, 7,* Dicembre, 1913.

"How we ought to protect ourselves from earthquakes." By G. Agamennone. (Reprint from the *Revista de Astronomia e Scienze Affini* of December 1913.)

The author of this article, recalling the numerous earthquakes from which Italy has suffered, concludes that earthquakes should be expected and prepared for.

Seismologists who have studied the question have shown that, of themselves, earthquakes are comparatively harmless. Improper construction or bad situation of buildings has been the main cause of disaster. Man builds to protect himself from snow, rain, etc., but not from earthquakes.

Two kinds of protection have been suggested: 1. Property owners can be compensated for losses by public benevolence or by some form of insurance. 2. Damage to property and loss of life can be prevented by proper construction of buildings.

After various earthquakes steps have been taken to insure proper reconstruction, but regulations formulated have been disregarded because of the expense involved and because of the seeming remoteness of the danger.

The author quotes suggestions by previous writers, such as government inspection of buildings, maintenance of companies for rescue work, insurance against earthquakes, etc. He thinks the state could insure against earthquakes, as private companies have not entered this field. He thinks the government should create a department with its minister, its activities to be devoted to attenuating damage caused by earthquakes, volcanic eruptions, conflagrations, floods, and the like. Money and administrative apparatus would then be at hand for saving life and property. The budget for this department could be provided for as, for example, in the budget of the war department. This, with severe regulations regarding the repair and reconstruction of buildings, would remove many of the disastrous results of earthquakes, and would make it unnecessary for a nation to be humiliated by receiving alms from abroad.

C. G. ALLEN.

EARTHQUAKES IN EAST TENNESSEE. By C. H. Gordon. *The Resources of Tennessee,* 4, 15-23, (Nashville), January 1914.

This paper refers only to the shocks of March 28 and April 17, 1913, both of which were described by Professor Gordon in this BULLETIN.[1] There are added some remarks on the cause and nature of earthquake phenomena. J. C. B.

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[1] *Bulletin of the Seismological Society of America,* 3, 191-194.

SEISMOLOGICAL REPORTS RECEIVED.

AMERICA

Harvard University, Cambridge, Mass., U. S. A.—Records of the seismographic station, nos. 8 to 13, April 24, 1914, to August 28, 1914.

Denver, Colorado, U. S. A. Jesuit Seismological Service.—Earthquake station, Sacred Heart College, nos. 1 to 5, January 1 to May 31, 1914.

Santa Clara, California, U. S. A. Jesuit Seismological Service.—Seismographic station, University of Santa Clara, nos. 125 to 133, January 24 to August 22, 1914.

Ottawa, Canada. Earthquake station, Dominion Astronomical Observatory.—Reports nos. 3, 9 to 18, May 26, 1914, to August 31, 1914.

PHILIPPINE ISLANDS

Manila, P. I.—Seismological Bulletin of the Observatory, nos. 16 to 21, May 1 to June 30, 1914.

Catalogue of Philippine earthquakes, 1913.—Reprint from the *Weather Bureau Bulletin* for December 1913. 3 pages.

EUROPE

Stonyhurst College Observatory.—Earthquake records by Milne seismograph. March 27 to August 28, 1914.

Granada, Spain.—Boletin mersual de la Estacion sismologica de Cartuja. Nos. 4 and 5, April and May 1914.

Nachrichten des Taunus-Observatoriums des phys. Vereins zu Frankfurt am Main.—Nos. 3 and 4. March 6 to April 20, 1914.

Monatsberichte der Hauptstation für Erdbebenforschung zu Jena. June 29 to September 28, 1912.

ASIA

Zi-ka-wei (China).—Bulletin Sismique, nos. 3 to 6 bis. March 4 to May 27, 1914.

Observatoire de Ksara.—Bulletin Sismique, December 31, 1913, to June 6, 1914.

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

I. **Microseismic shock**: recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. **Extremely feeble shock**: recorded by several seismographs of different kinds; felt by a small number of persons at rest. some startled persons leave their dwellings.

III. **Very feeble shock**: felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. **Feeble shock**: felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.

V. **Shock of moderate intensity**: felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.

VI. **Fairly strong shock**: general awakening of those asleep, general ringing of house bells; oscillation of chandeliers; stop-

VII. **Strong shock**: overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. **Very strong shock**: fall of chimneys. cracks in walls of buildings.

IX. **Extremely strong shock**: partial or total destruction of some buildings.

X. **Shock of extreme intensity**: great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

The Bulletin of the
Seismological Society of America

VOL. IV DECEMBER, 1914 NO. 4

ON THE EARTHQUAKES OF 1868 IN HAWAII

By Harry O. Wood

The earthquakes which occurred in the Island of Hawaii in the spring of 1868 have been considered, almost without reservation, shocks of volcanic origin. This was the view of all local investigators, and it was the general conclusion reached in 1869 by Dr. W. T. Brigham.[1] Dana,[2] after a remarkably clear-sighted statement of the chief facts, gave this interpretation of them. Dutton, who studied the Hawaiian volcanoes in 1882,[3] then considered these to be shocks of the volcanic type,—a judgment which much later, in his "Earthquakes",[4] he reaffirmed emphatically and unequivocally. Even very recently Professor C. H. Hitchcock, who has long been interested in Hawaiian volcanic phenomena, has expressly declared[5] in favor of this view. This opinion has been, and is, current among the thoughtful and intelligent residents of the Hawaiian Islands, and it is a received view among geologists and seismologists. Indeed, it is doubtful if any alternative view has been thoughtfully considered.

Unquestionably these earthquakes were contemporaneous with great activity in the summit-sink-craters of both Kilauea and Mauna Loa—activity which culminated in the bursting of lava flows out of fissures rent open low on the flanks of *both* these mountains, as Professor Hitchcock has recently pointed out. Furthermore, it is reliably testified that the strongest shock of the series occurred at the time when the Kilauean flow burst forth.

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[1] "Notes on the Eruption of the Hawaiian Volcanoes, 1868." *Memoirs Boston Society Natural History,* 1, iv, 1869. (In conversation, Dr. Brigham not long since stated to the writer that he has come to think these shocks due, in part at least, to so-called tectonic agencies.)

[2] "Characteristics of Volcanoes." Dodd, Mead & Co., New York, 1891, pp. 231-234.

[3] "Hawaiian Volcanoes." Fourth Annual Report U. S. Geological Survey, 1882-83, pp. 75-219.

[4] "Earthquakes—In the Light of the New Seismology." G. P. Putnam's Sons, 1904, p. 45.

[5] "The Hawaiian Earthquakes of 1868." *Bulletin Seismological Society of America,* 2, 181-192.

Nevertheless, as all these writers have stated, Dana with especial clearness, the eruptions on this occasion were unusual in several respects, being particularly remarkable for this accompaniment of strong earthquakes in great number. Indeed, if we take account of the amount of energy displayed on this occasion, these earthquake-eruptions occupy an unique position in the history and tradition of Hawaii. However, we must not overlook the fact that all the eruptions which have sent forth flows from rents on the southwest flank of Mauna Loa, in 1887 and in 1907 (as well as in 1868), have been accompanied by a sequence of shocks similar in way of occurrence to these of 1868 —though by no means approaching them in intensity or total energy.

Now, if earthquakes of the volcanic type are to be defined simply as those which occur in association with the eruption of volcanoes, then there could be no question about the series here considered. But there *is* another side to this shield. Shocks of the volcanic type are considered to be *caused* by the action of forces resident in the molten magma cistern and its conduits, commonly thought of as rapid expansions in the molten body, and usually referred to imprisoned gases. Some geologists, possibly a large number, among them the writer, are skeptical of such a mode of causation limited thus narrowly. But such an opinion is still prevalent and formerly was accepted without reserve.

It has been generally allowed—by some very able seismologists the point has been insisted upon—that volcanic shocks, as thus defined, though sometimes intensely destructive in their epifocal tracts, have shallow origins and develop relatively little energy when compared with destructive shocks of the tectonic type. Dr. C. Davison, treating of the earthquakes in Ischia throughout its history considers these to differ from tectonic shocks in that they have been characterized by (1) coincidence of epicenters, (2) shallow depths of the foci, and (3) the suddenness of the (arrival of the main) shocks. By these same tokens he considers them volcanic shocks. Also Dutton himself says: "Volcanic quakes, so far as we are sure of their origin, are seldom felt at great distances from their epicentres, even though their violence near the epicentre may be very great. The meaning of this . . . is that the forces from which they originate are shallow." And he also cites the utter destruction of Casamicciola in Ischia, "only one house . . . left standing, and the number of people killed by the falling ruins . . . nearly 1900. Yet in Naples, *only twenty-two miles distant,* the shock was noticed by only a few people as a faint tremor."

While possibly it has never been intended explicitly to deny that shocks of volcanic type may emanate from deep sources and develop great amounts of energy, still it has come to be a generally received concept that such shocks do not possess these characteristics. Moreover, hypotheses of explosive expansions involving large, rapid volume changes at great depths, whether considered due to the action of imprisoned gases or to sudden tumefaction of the magma itself, would appear to entail considerable physical difficulties. Therefore, with these definitions and ideas in mind, it will be well to review at some length the available accounts of this 1868 series of shocks in Hawaii.

In the comments which follow the writer particularly wishes to avoid the semblance of writing dogmatically, or of arguing in a contentious way in support of a fixed opinion. But he thinks it will shed new light on this sequence of events if the evidence, old and new, is presented as though a tectonic origin for these shocks were possible—and possibly even more probable than a strictly volcanic origin as above defined. However, wherever unqualified, assertive comments are made it is only to avoid wearisome circumlocutions. By *tectonic origin* the writer here means, origin upon a fracture or fault-slip, or a system of these, resulting from a culmination in the regional elastic strain in the rock crust, the grating and grinding relief of a regional shear or warp.

In connection with such a contingent view let it be recalled that Dana, whose study of Hawaiian volcanic processes has proved more illuminating than that of any other man as yet, held the following view in regard to the genesis and association of these volcanoes:—

> The *occurrence of volcanoes in long lines* implies dependence as to origin on great fractures and mutual dependence of the volcanoes along any such lines. The lines are often in parallel ranges or series of fissures, and must have opened through the earth's crust to the depths that supplied the melted rock. In some cases the volcanic action along such lines has continued longer at one end of the line, or of the several lines in a series, than at the opposite end, and extinction has been in like manner serial. An example is afforded by the Hawaiian group.

Dana does not explicitly state whether he regards these major fissure systems as produced by volcanic forces or agencies. It is legitimate to infer from the context that he does so consider them.

However, it is now usual to regard such great fractures as he has referred to as of the major tectonic kind due to orogenic or epeirogenic stresses accumulated until competent to rend the crust to great depths. It must, of course, be understood that here we are not inquiring into the causes of tectonic stresses. If these are everywhere closely linked with, or anywhere exclusively or chiefly due to volcanic processes we have yet to ascertain and establish such a relationship. Ordinarily they are considered to arise from a great complex of forces working concurrently, in some cases involving volcanism.

If major tectonic strains have been building in this region in the past, as seems to have been the case, there certainly is no warrant for rejecting the hypothesis that such strains may yet be building here, and still attaining temporary relief by fresh fracturing or slipping. A good deal, of course, could be said in favor of such a view.

Let us now examine the record of the series of shocks, largely extracts from letters and news-items in the Honolulu press of 1868, a press then served by written communications from correspondents, before the local introduction of telegraph or cable, and consequently a very reliable source of information.

The abstracts have been arranged under headings to develop the facts systematically.

The maps, Figures 1 and 2, show the districts and localities so frequently referred to.

EARLIEST SYMPTOMS OF THE DISTURBANCE

The Volcanic Prelude at Kilauea.

. . . Now allow me to relate what I learned from Kaina (the District Judge and a most intelligent Hawaiian), who has resided near the volcano (Kilauea) without interruption for the last five months. . . . He says that for two months preceding the first shock, namely, from January 20th to March 27th, the crater had been unusually active, eight lakes being in constant ebullition, and frequently overflowing. During all this time (the date of its first appearance could not be ascertained exactly), there was in the northwest corner a "blow-hole," from which, at regular intervals of a minute or less, with a roaring noise, large masses of vapor were thrown off, as from a steam engine. This ceased about the 17th of March. At the same time the activity of the lakes became greatly increased. . . . March 27th, the first shock was perceived. . . . —*From a letter of Dr. William Hillebrand, Honolulu, May 4, 1868.*

At Kilauea.

. . . Just before the Great Earthquake of April 2, 1868, there were twelve lakes in active operation, besides many cones. On the night of the 2nd of April (after the earthquake.—Ed.) the appearance of the crater was grand beyond description, nearly the whole surface being covered with the liquid lava. . . . —*Entry in Volcano House Record-Book,* (*signed*) *C. E. Stackpole.*

The Volcanic Prelude at Mauna Loa. The following is the first mention of *volcanic outbreak* encountered. From the Kohala District.

The great mountain of Mauna Loa has again commenced to display its wonderful volcanic fires. On Thursday night (March 26th), from Kawaihae was seen that first glimmer of light from the new opening on the mountain's side, which soon lighted up the heavens and indicated that a new lava flow had

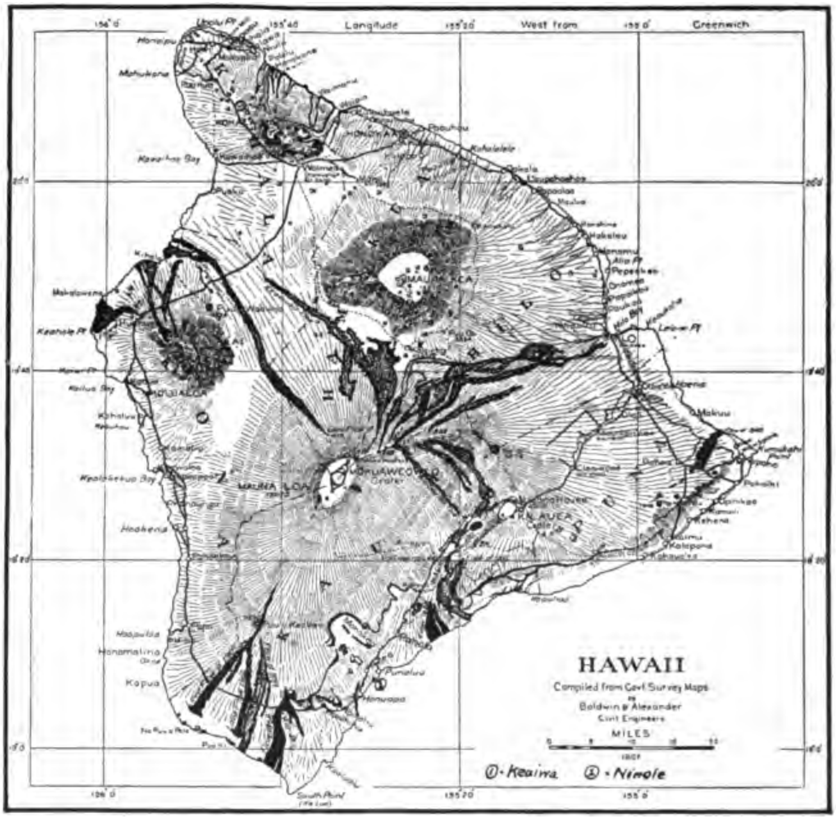

Fig. 1. The Island of Hawaii.

begun. The crater seems to be near that of 1859, and the lava to flow in a northwesterly direction toward the sea. It can be seen distinctly from the beach with the aid of a good glass. . . . —*From the Hawaiian Gazette, Wednesday, April 1, 1868.*

However, a Kau opinion, of the 29th of March, is as follows:

> . . . We are inclined to believe that the lava has not yet broken out (plainly meaning through the flank or side of the mountain.—Ed.) but that the light seen is from the lakes which have opened in the great crater of Mokuaweoweo.—*Item in the Pacific Commercial Advertiser, April 4, 1868.*

The above is plainly an inference, from previous experience, as to the manner of eruption of Mauna Loa. For, owing to the great bulk of the mountain, and the flat top of its dome, its summit is not visible from points along this part of the island shore or low down on the mountain flanks.

However:

> An intelligent native who slept at the Volcano House on Monday night, the 30th ult., (from which place the whole flank of Mauna Loa, to beyond Kapapala and Waiohinu, is visible), saw no lava streams on that night.—*Item in Hawaiian Gazette, April 9, 1868.*

Nevertheless, a letter of F. S. Lyman, dated March 31st, from Kau, near Kapapala, stated:

> . . . You may have already heard that an eruption broke out on Mauna Loa, a little to the southwest of the summit, about 6 o'clock last Friday morning, 27th inst. It gave no forewarning, the fire burst up out of the ground, throwing a spray of red lava high in the air, then a great column of smoke rose straight up thousands of feet and arched over to the east. In a few minutes a new jet was thrown up a little S.E. of the first, with its column of smoke, soon followed by another jet, and then by a fourth; soon the red lava began running down the sides of the mountain in four streams in a southerly and westerly direction. About seven o'clock we began to hear a roaring sound, which grew louder and louder until the air seemed to tremble with the incessant roar of the volcano; but it finally subsided and ceased entirely about eight o'clock. (Note.—The jets of red lava referred to above must have spurted to a considerable altitude to have been so plainly seen by Mr. Lyman from his place of residence.—Ed.)
>
> Saturday morning (March 28th), we could see smoke, and the flow had apparently run about ten miles to the south from the source, but during the day and part of the night it was covered with clouds.
>
> Sunday morning (March 29th), the line of smoke had advanced about fifteen miles, since the morning previous, and seemed to be distinctly mauka

(towards the summit) of Capt. Brown's place on Kahuku, ***but what seems singular, from the beginning, no light has been seen from it anywhere, excepting at the source and what was seen to flow, only the line of smoke has been visible since with an occasional vision of light at the source.***

In the forenoon of Friday (March 27th), the day the volcano broke out, we had quite a little sprinkling of Pele's Hair. . . . —*Published in The Pacific Commercial Advertiser, Saturday, April 18, 1868.*

The foregoing account is authentic, from the pen of an eyewitness, and is circumstantial; furthermore the portion italicised by the present writer suggests an explanation of the two preceding abstracts. Also it is supported in essentials by the following accounts.

A letter of the Rev. C. G. Williamson from the Kona District, dated March 31st, is abstracted as follows:

. . . On Friday morning last (March 27th), an indication of a new eruption on Mauna Loa, a thick volume of smoke being observed, rising from some unseen opening in the earth. I first observed it at 5:45 a.m. It then appeared something like a fan, and had evidently not been visible for more than a quarter of an hour or so previously. Very quickly the smoke spread and wrapped the mountain in a black cloud of vapor. There was no appearance, as far as I could judge, of any fire. It was with impatience that the night was desired, when it might be seen whether there was any indication to show that lava was flowing; however, when the mountain wind had dispersed the pillar of cloud, everything appeared quite natural and no fresh smoke seemed to be emitted. Saturday morning (March 28th), just before sunrise, the smoke, rising from some hidden orifice, again showed itself, and the conviction grew that some new volcanic agency was at work. . . . —***Published in the Hawaiian Gazette, April 8, 1868.***

Extract from a letter dated Kona, March 28, 1868:

. . . Yesterday morning, March 27th, we had a glorious sight from our verandah. About twenty minutes before six o'clock we discovered on the summit of the mountain (Mauna Loa) an immense mass of smoke rising high in the firmament with high pillars resting upon it. In less than half an hour vast columns of smoke were rising in a southerly direction, to the distance of ten or fifteen miles.—*From the Pacific Commercial Advertiser, April 11, 1868.*

The following early news-item, not to be taken as strictly accurate, is also of interest.

. . . The eruption occurred on the very summit of Mauna Loa, at a place known as Pohaku, Hanalei, and threw up five different jets, and three streams are said to be flowing—one towards Kona, south of Kealakeakua, near Kahuku; another towards Kapapala (Reed & Richardson's ranch); and the third near Punaluu, all down towards the south point of the island.—*From the*

Pacific Commercial Advertiser, under headline *Postscript—Latest from the Volcano—in the issue of Saturday, April 4, 1868, from information transmitted before the occurrence of the strongest earthquake.*

Careful study of all our records of the volcanic action of Kilauea and Mauna Loa develops clearly that on this occasion *both volcanoes* were unprecedentedly active *before* the culminating shocks of earthquake, that Kilauea had been very unusually active for some months prior to the event, and that the activity in its *open* crater was greatly increased within a few days before the occurrence of the strong shocks. Mauna Loa, as it happened, broke into action, since it is frequently dormant, but it did so at a time of great and increasing activity in Kilauea, and before the series of *frequent* shocks began, as we shall see below. In all respects this behavior of the two volcanoes in conjunction was unusual, in some respects unprecedented, and so contrary to ordinary expectation. To interpret the events as strictly volcanic occurrences and phenomena is possible, of course, but as stated above it seems profitable to examine another view.

THE SEQUENCE OF EARTHQUAKES.

Foreshock Phenomena (?):

> . . . The mountain (Mauna Loa) has been giving symptoms of uneasiness for some weeks past. On Monday, the 8th ult. (probably a journalistic error for Monday, March 9, 1868.—Ed.), a hard shock of earthquake passed through the Kona district. . . . —*News item in the Hawaiian Gazette, April 1, 1868.*

BEGINNINGS OF THE SEISMIC SPASM

District of Kau. A letter of the *29th of March* says:

> At about 8 o'clock Friday evening, (March 27th) we felt a slight shock of an earthquake; this was the first and *possessed some novelty.* Since then we have had no less than three hundred. . . .
>
> . . . The most severe shock took place at a quarter of two o'clock yesterday afternoon (Saturday, March 28th). The earth moved like a troubled sea, and the wonder is that more damage was not done.—*From the Pacific Commercial Advertiser, April 11, 1868.*

Can the above phrase italicised by the present writer be taken to imply total absence of premonitory quivers in Kau, or is it merely rhetorical? In view of the statement immediately above the writer is inclined to the latter opinion.

This shock of March 28th may be regarded as the *first culmination* in this seismic spasm.

A correspondent, writing from Kau, says:

> The earthquakes commenced on Friday night (March 27th); some say we had thirty or more shocks. Saturday morning I awoke about daylight, and up to 1 p.m. I counted ninety-seven earthquakes; none were severe, but their frequency frightened us; while at dinner (probably about 1:30 p.m. local time.—Ed.) we had a heavy shock. . . . In less than twenty-four hours we had over two hundred shocks!—*From The Pacific Commercial Advertiser, April 11, 1868.*

District of Kona. From letters of the Rev. G. G. Williamson, from near Kealakekua:

> Christ Church, Kona, Hawaii, *March 31st*, 1868.
>
> . . . After two or three delicate hints we were first startled by a distinct shock of earthquake which occurred at 10:15 a.m. (Saturday, March 28th). From that time up to the time of sending this letter, a period of three days and a half, we have had 123 distinct shakes, some being more violent than others. Saturday, the 28th of March, . . . there were 51 decisive shocks, one of which was the strongest earthquake that the oldest habitant has experienced. (Up to the time of the writing of this letter.—Ed.) . . . This occurred at 1:28 p.m. . . .
>
> . . . As you will observe in my list, there is no shock noticed as taking place between 10:27 p.m., Saturday night, and 1:10 a.m., Sunday morning, although I hear from others that there were continued shocks at about the same intervals as during the day.
>
> At ten minutes past one, on Sunday morning, I was suddenly awoke by a strong shake, which was calculated to startle the soundest sleeper. . . . I missed several lighter shocks, which, to make a complete list, ought to be reckoned. Of the shocks experienced by myself on Sunday, there were 51—by a remarkable coincidence, a corresponding number to those on Saturday. The number of vibrations on Monday was much less, only 12 shocks occurring. To-day (Tuesday), up to the time of my writing this, it being now 6 p.m., we have only felt nine shakes, a number small in comparison with the earthquakes of Saturday and Sunday. As I remarked before, these shocks were more or less severe, but all were decided. The following list I copy from my Diary, which, along with my watch, I have kept at hand, so that I might be as accurate as possible in my statement. . . . —*Published in Hawaiian Gazette, April 8, 1868.*

Below the present writer has arranged this list of Mr. Williamson's, together with those of succeeding letters from him, published also in the *Gazette,* in convenient tabular form. The times given are local times determined by Mr. Williamson's watch. He classified the shocks, as to intensity, in the following way:

INTENSITY CLASSIFICATION—WILLIAMSON

VL = Very light
L = Light
M = Moderate
H = Heavy
VH = Very heavy
VVH = Very, very heavy

Date	Hour	Intensity	Date	Hour	Intensity	Date	Hour	Intensity
Mar. 28	10:15 a.m.	M	Mar. 28	8:07 p.m.	VL	Mar. 29	8:48 a.m.	M
	1:15 p.m.	M		[3] 8:45 p.m.	L		9:02 a.m.	M
	1:22 p.m.	VH		9:04 p.m.	MH		9:15 a.m.	M
	[1] 1:28 p.m.	VVH		9:14 p.m.	VL		9:22 a.m.	L
	1:51 p.m.	M		9:27 p.m.	L		9:58 a.m.	L
	2:15 p.m.	L		9:35 p.m.	MH		10:13½am	L
	2:17 p.m.	L		9:39 p.m.	L		11:23 a.m.	L
	2:32 p.m.	L		9:50 p.m.	L		11:37 a.m.	L
	[2] 2:50 p.m.	L		10:02 p.m.	L		11:44 a.m.	L
	2:57 p.m.	L		10:17 p.m.	H		12:12 p.m.	M
	3:04 p.m.	L		10:22 p.m.	L		12:22 p.m.	M
	3:16 p.m.	L		[4] 10:27 p.m.	L		12:25 p.m.	L
	3:18 p.m.	L					1:09 p.m.	H
	3:20 p.m.	L	Mar. 29	1:10 a.m.	VH		1:21 p.m.	L
	3:26 p.m.	L		1:11 a.m.	M		1:30 p.m.	M
	3:27 p.m.	L		[5] 2:24 a.m.	H		1:40 p.m.	L
	3:30 p.m.	H		3:30 a.m.	L		1:46 p.m.	L
	3:36 p.m.	L		4:00 a.m.	H		3:00 p.m.	L
	3:50 p.m.	L		5:00 a.m.	H		3:09 p.m.	L
	4:00 p.m.	H		5:02 a.m.	L		3:11 p.m.	L
	4:02 p.m.	L		[6] 5:36 a.m.	H		4:32½pm	VL
	4:10 p.m.	L		5:45 a.m.	L		4:52 p.m.	L
	4:15 p.m.	VH		6:08 a.m.	L		7:08 p.m.	L
	4:30 p.m.	L		6:30 a.m.	L		7:51 p.m.	M
	4:35 p.m.	M		6:45 a.m.	L		8:45 p.m.	VL
	4:37 p.m.	M		6:57 a.m.	M		[7] 9:00 p.m.	VL
	4:39 p.m.	M		7:03 a.m.	Long and moderate			
	4:50 p.m.	M				Mar. 30	1:00 a.m.	VH
	5:00 p.m.	M		7:30 a.m.	L		1:30 a.m.	L
	5:05 p.m.	M		7:32 a.m.	M		6:11 a.m.	M
	5:08 p.m.	H		7:33 a.m.	M		7:18 a.m.	M
	5:40 p.m.	M		7:35 a.m.	M		2:20 p.m.	VL
	6:00 p.m.	H		7:40 a.m.	M		7:12 p.m.	M
	6:37 p.m.	M		7:53 a.m.	L		8:18½pm	M
	6:40 p.m.	M		8:03 a.m.	L		8:45 p.m.	M
	6:48 p.m.	M		8:06 a.m.	L		8:56 p.m.	VL
	7:05 p.m.	M		8:10 a.m.	VL		9:01 p.m.	VL
	7:20 p.m.	M		8:30 a.m.	L		9:28 p.m.	L
	7:48 p.m.	L		8:39 a.m.	L		11:35 p.m.	H

FOOTNOTES TO MR. WILLIAMSON'S LIST OF SHOCKS

By Williamson, except as noted.

[1] This lasted some time, causing everything to rock backward and forward.

[2] From 2:50 p.m. until 4:00 p.m. the ground was incessantly rocking, being occasionally relieved by a more decisive shake, which I have noticed.

[3] Light, but of a distinctive character; hitherto all the shocks have been of the character known as horizontal vibrations, but this shock had a vertical movement, and during its continuance presented the idea of attempt being made to lift the house from underneath. It happened during the hour for family worship, and the leg felt suddenly cramped below the knee.

[4] At this time I retired to rest and slept until Sunday morning (March 29th), when awoke at 1:10, very heavy shock with continual trembling of the ground for one minute, ending with a moderate shock at 1:11 a.m.

[5] Slept again and awoke at (this time).

[6] Lasted about thirty seconds

[7] This is the total of those (shocks) felt by me on this day.

Date	Hour	Intensity
Mar. 31	1:58 a.m.	M
	3:30 a.m.	M
	3:43 a.m.	L
	3:50 a.m.	L
	4:20 a.m.	L
	5:07 a.m.	M
	5:22½am	H
	9:20 a.m.	L
	4:43 p.m.	M
April 1	[8] 1:45 a.m.	M
	5:40 a.m.	H
	[9] 6:00 a.m.	L
End of first list		
April 1	[10] 8:15 p.m.	M
	8:30 p.m.	M
	9:21 p.m.	MH
	10:25 p.m.	H
	[11]10:53 p.m.	M
	[11]11:00 p.m.	H
	[11]11:08 p.m.	VH
	11:10 p.m.	M
	11:12 p.m.	H
	11:14 p.m.	H
	11:16 p.m.	L
	11:18 p.m.	M
	11:19 p.m.	M
	11:26 p.m.	M
	11:30 p.m.	M
	[12]11:31 p.m.	H
	[12]11:50 p.m.	H
April 1	[13]11:51 p.m. to [13]12:00 p.m.	....
April 2	12:06 a.m.	L
	12:20 a.m.	M
	12:35 a.m.	H
	12:37 a.m.	L
	12:40 a.m.	L
	12:43 a.m.	M
	[14]12:53 a.m.	M
	9:40 a.m.	L
	2:45 p.m.	L
	[15] 3:40 p.m.	Terrific shock
	4:15 p.m.	M
	4:25 p.m.	M
	5:09 p.m.	L
	5:45 p.m.	L
	5:48 p.m.	L
	5:50 p.m.	M
	5:57 p.m.	M
	6:27 p.m.	M
	6:32 p.m.	L
	6:40 p.m.	M
	8:07 p.m.	MH
	9:45 p.m.	M
	10:26 p.m.	L
	11:03 p.m.	MH
April 3	12:24 a.m.	MH
	1:05 a.m.	L
	1:25 a.m.	M
April 3	1:45 a.m.	VH
	2:33 a.m.	H
	5:45 a.m.	H
	6:05 a.m.	L
	7:44 a.m.	M
	8:32 a.m.	L
	11:02½am	L
	4:20 p.m.	L
	5:43 p.m.	L
	6:02 p.m.	L
	6:15 p.m.	L
	7:02 p.m.	L
	[16] 7:35 p.m.	....
	[16] 7:47 p.m.	....
	[17] 7:53 p.m.	L
	8:25 p.m.	M
	8:33 p.m.	M
	9:25 p.m.	H
	11:53 p.m.	H
April 4	12:07 a.m.	VH
	12:12 a.m.	VH
	12:29 a.m.	VVH
	12:45 a.m.	H
	4:40 a.m.	L
	5:55 a.m.	L
	6:33 a.m.	M
	7:14 a.m.	L
	10:15 a.m.	M
	2:01 p.m.	M
	2:09 p.m.	M
	5:55 p.m.	M
	[18] 8:51 p.m.	M

---

[8] Wednesday morning (April 1st). I add a P. S. to say that during last night five distinct shocks were experienced by members of my household. I was aroused by one which happened at 1:45 a.m. It was a moderate shock.

[9] This ends the first of Williamson's letters, published in the *Hawaiian Gazette,* April 8, 1868.

[10] Beginning of second Williamson letter:

"South Kona, Hawaii, 7th April, 1868.

" . . . I again offer you my list, with this remark: each shock noticed by me was a decided shake. I do not claim to notice every vibration that has happened, for many felt by others during the night have passed unnoticed by me. I give you the list as perfect as I can, vouching for accuracy in my statements. . . . "

[11] Accompanied with the sound of an explosion.

[12] From 11:31 to 11:50 continual explosions followed by shocks of moderate severity. (It is not unlikely that these sounds of *explosion* were deep, grave booming noises, such as are commonly heard accompanying the shocks of major seismic events.—Ed.)

[13] Same as from 11:31 to 11:50.

[14] At 1 a.m. a heavy rain came on and I experienced no shock until morning.

[15] (A considerable narrative concerning this great shock, quoted and so utilized in another part of this paper.—Ed.)

[16] Explosion without shocks. (Cf. above under [12].) [17] Light and vertical.

[18] Three shocks between Saturday and Sunday; I did not get the time.

Date	Hour	Intensity
April 5	3:35 p.m.	L
	3:55 p.m.	L
	6:44 p.m.	M
	7:25 p.m.	M
	7:30 p.m.	L
	8:11 p.m.	VL
April 6	9:45 a.m.	L
	1:59 p.m.	L
	2:34 p.m.	M
	2:53 p.m.	H
	4:09 p.m.	L
	4:10 p.m.	L
	4:15 p.m.	L
	4:17 p.m.	L
	4:18 p.m.	L
	4:21 p.m.	L
	4:24 p.m.	L
	4:33 p.m.	L
	6:00 p.m.	VL
	6:10 p.m.	M
	[19] 7:29 p.m.	....
	7:54 p.m.	VL
	[20] 8:50 p.m.	....
	[20] 8:54 p.m.	....
	9:47 p.m.	L
	9:58 p.m.	L
April 7	1:00 a.m.	L
	1:15 a.m.	L
	2:10 a.m.	H
	3:55 a.m.	M
	4:00 a.m.	M
	4:08 a.m.	M
	4:20 a.m.	L
April 7	4:40 a.m.	M
	5:00 a.m.	H
	5:45 a.m.	L
	6:00 a.m.	L
	11:16 a.m.	L
	11:33½am	M
	12:00 m.	MH
	12:06 p.m.	MH
	12:09 p.m.	MH
	12:13 p.m.	L
	12:20 p.m.	L
	12:55 p.m.	L
	1:02 p.m.	L
	1:50 p.m.	L
	1:57 p.m.	MH
	2:00 p.m.	L
	[21] 2:18 p.m.	H
	2:54 p.m.	L
	3:08 p.m.	L
	3:11 p.m.	L
	3:12 p.m.	M
	3:17 p.m.	M
	3:20 p.m.	M
	3:32 p.m.	L
	3:41 p.m.	M
	4:00 p.m.	M
	4:07 p.m.	L
	4:08 p.m.	L
	4:20 p.m.	MH
	4:32 p.m.	L
	7:26 p.m.	H
	8:21 p.m.	M
	10:33 p.m.	L
	11:05 p.m.	H
April 8	[22] 5:30 a.m.	H
End of second list.		
April 8	[23] 8:25 a.m.	L
	[23] 12:12 p.m.	....
	[23] 5:41 p.m.	....
	[23] 9:03 p.m.	....
April 9	[24]	....
April 10	6:02 a.m.	H
	6:40 a.m.	L
April 11	[25] 5:40 a.m.	MH
April 12	[26] 6:57 a.m.	....
	9:55 p.m.	M
April 13	[27] 9:53 p.m.	....
April 14	6:44 a.m.	M
	5:14 p.m.	M
April 15	[28] 8:05 p.m.	MH
April 18	10:50 p.m.	M
April 19	12:00 p.m.	M
April 20	8:45 p.m.	L
April 21	6:30 a.m.	L
	7:58 a.m.	MH
End of third and last list.		

[19] An explosion. (Cf. above under [12].)

[20] Explosion and shake. (Cf. above under [12].)

[21] Light with explosion.

[22] End of second Williamson letter and second list, published in the *Hawaiian Gazette,* April 15, 1868.

[23] Beginning of third Williamson letter:

"Kona, Hawaii, 14th April, 1868.

" . . . 8:25 a.m. . . . Wednesday, 8th April . . . light, accompanied with a rushing sound;

"12:12 p.m., long, and distinct motion;

"5:41 p.m., same as last;

"9:03 p.m., distinct movement of the earth."

[24] Thursday, 9th (April), a few slight undulations, but no distinct shocks.

[25] Saturday, 11th (April), 5:40 a.m., moderately smart shock.

[26] Sunday, 12th (April), 6:57 a.m., two successive shakes.

[27] Monday, 13th (April), 9:53 p.m., a distinct rumble in the earth.

[28] Immediately following the entry for April 14th is a note dated April 21st, which states, "While I was away I was unable to note the occurrence of shocks, but I have the following:" then follow the six shocks tabulated here.

The foregoing list of shocks is the most complete specific list of this group that we possess. However, the following statements are of interest:

> The earthquakes which commenced on Saturday (March 28th), were felt simultaneously in Kona, Kau and Hilo (probably throughout these districts.—Ed.). At the latter place there were thirty shocks from Saturday to Monday. *—Regular news paragraph, Hawaiian Gazette, April 1 (?), 1868.*

But with regard to the *number* of shocks see the following letter, from a place in the Hilo district north of Hilo town:

> Kaupakuea, Hilo, March 29, noon, (1868).
>
> Mother earth has been quite lively since yesterday. . . . There have been at least a hundred shocks during the last twenty-four hours—some tolerably violent. . . . Monday morning (March 30th)—the shakes continue—had one a minute ago.*—From the Pacific Commercial Advertiser, April 11, 1868.*
>
> Kealakekua, Hawaii, Monday, April 13, (1868).
>
> . . . The number of shocks which occurred at Waiohinu from March 29th to April 10th is estimated by Mr. Silloway to have been upwards of *two thousand,* there having been some days between three and four hundred. . . . *—From published letter of H. M. Whitney, Editor, to The Pacific Commercial Advertiser, April 18, 1868.*

THE SERIES OF AFTERSHOCKS

The following extracts tell of the shocks experienced after the "spasm" of March 28-April 7 was over:

> Several very light shocks have been felt here (Honolulu) during the past week, particularly on Thursday morning (April 30th), about 6 o'clock. On Maui a shock was felt about the same hour. At Hilo no very severe shocks had occurred for the ten days prior to the 28th of April, though occasionally very slight motions were perceived. The same shock was very severe at Kohala, occurring at 6:15 (a.m.)*—From The Pacific Commercial Advertiser, May 2, 1868.*
>
> . . . He (Mr. Richardson) reports Kau still shaking, and says one can feel a shock at any time by sitting down on the ground. The earth is continually in motion, but when walking about one does not notice it. On Sunday, May 3d, he counted eighteen very perceptible shocks. . . . *—From the Hawaiian Gazette, May 26, 1868.*
>
> There was a smart shock of earthquake at Hilo on the 9th instant. People ran out of their houses, and there was a great rattling of goods and chattels. *Shocks are frequent over the whole island of Hawaii, but usually very light.* . . . *—From the Hawaiian Gazette, May 19, 1868.*
>
> We learn from Judge Hitchcock, who has just arrived from Hilo, that the earth has by no means become quiet. Two, three and more earthquakes are daily experienced at Hilo, and through Kau. Reports from Kona indicate that the land is not at rest on that part of the island. . . . In Kau the trembling is very frequent, and sometimes severe.*—From The Friend, June 1, 1868.*

These extracts furnish at one and the same time adequate evidence of the continued occurrence of frequent shocks long after the culmination of the spasm—and of the occurrence of at least one later shock energetic enough to be felt on Maui and Oahu, presumably of deep origin and not emanating from beneath Kau (for it is mentioned as severe at Kohala, but not specially mentioned from southern Hawaii), whence the culminating shocks emanated.

Now it is the ordinarily received view that with shocks of the strictly volcanic type, however destructive in the epifocal tract, *after-shocks are very few and soon over*, because of the comparatively small size of the region of origin, its relatively small depth, and the comparatively small amount of the total energy of the disturbance. This constitutes one more implied criterion for this class of earthquakes.

Major Dutton, who believed that these Hawaiian shocks were of volcanic causation, considered that there were few or no after-shocks in this instance. He makes the statement[6] "From this time on (eruption of April 7), the earthquakes rapidly died away, and a day or two later everything was quiet."

In this opinion he was unquestionably in error. For the extracts above prove clearly that shocks, some of which were quite severe, continued to occur frequently throughout April and May,—and the last recorded mention of them is so phrased as to encourage the inference that the series was not yet completed.

Furthermore, a letter of the Rev. Titus Coan, one of the keenest and best-informed observers of volcanic events on Hawaii, addressed to Dr. W. T. Brigham, under date of *August 27*, 1868, contains the statement:

> . . . Our earthquakes still continue. Taking all parts of the island (Hawaii), they now average two or three a day; most of them are light. We have now had five months of constant disturbance. . . .

Therefore, in the matter of the sequence of the shocks, the circumstances of this event do not tally well with the generally accepted criteria of a group of volcanic earthquakes. On the other hand, though individual peculiarities are obvious, this series of shocks does correspond satisfactorily with the ordinary cycle—fore-shocks, main shocks and after-shocks—of great tectonic earthquakes. And here, as one of this class in which several main shocks of great power occurred, may be cited the New Madrid shocks of 1811-12.

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[6] "Earthquakes—In the Light of the New Seismology," p. 46.

THE DEGREE AND DISTRIBUTION OF APPARENT INTENSITY

As we have seen, there are three, possibly four, shocks or crises, in this series of earthquakes, which demand individual attention.

All accounts agree in indicating that *on land* the chief shock, at about 4 p.m. on April 2nd, was most severe in the District of Kau, on Hawaii; that it was very strong indeed in South Kona and in Puna; and, further, that there is strong suggestion that the energy in the neighborhood of the village of Hilo—and thence southwestward in the direction of Kilauea and Waiohinu—was but little less than in Kau. Of course, in a general way, this fixes the region of origin of many, probably a great majority, of the shocks.

A previous shock, early in the afternoon of March 28th, was energetic enough to be destructive. This shock, also, was most severe in Kau, particularly in the southern part of this district.

There was a shock, or several shocks in a group, in the night of April 3-4, felt distinctly in all the islands of the group. There is strong suggestion that these originated further north, or northwest, than the region of Kau.

Also, though little specific information has come to the writer's attention, owing probably to the disastrous character of the previous events, there probably occurred one or more strong shocks, originating beneath southern Kau, at the time of the outbreak of lava from the flank of Mauna Loa above Kahuku on April 7th. There is one account which asserts that the lava came out quietly.

THE SHOCK OF MARCH 28, 1868

At Kealakekua, Kona:

> . . . Saturday, the 28th of March, . . . there were 51 decisive shocks, *one* of which was the strongest earthquake that the oldest inhabitant has experienced. The force of it was seen in its throwing down a portion of Kealakekua Pali, and overturning stone walls in certain places. This occurred at 1:28 p.m. . . . —*From Williamson's letter, dated March 31st, in the Hawaiian Gazette, April 1, 1868.*

At Kona:

> . . . Stone walls were overthrown, masses of rock thrown off the pali (cliff) at the bay, and buildings seriously strained so as to alarm their inmates. Some stone buildings were rendered unsafe. The cisterns of the Kona Plantation were cracked so as to be unfit for service without repair. Some families were afraid to sleep at night, and kept their clothing on, ready to rush out of

doors at a moment's notice. . . . —*From Hawaiian Gazette, April 8 (?), 1868.*

In Kau:

. . . Waiohinu, Kau, however, seems more seriously shaken than Kona. The accounts from there, thus far (before the event of April 2d) indicate a state of alarm by no means pleasant to endure. . . .

The shaking of Saturday and Sunday (March 28th and 29th) was demoralizing to steady nerves. The stone house of Captain Brown, at Kahuku, was destroyed, the family barely escaping. The chimney of the mission parsonage was thrown down, and the walls of the stone church cracked. On Sunday Rev. J. F. Pogue held his service under a tree, deeming it unsafe to have his congregation inside the church.—*From Hawaiian Gazette, April 8, 1868.*

At Waiohinu:

Captain Haley's and Mr. Spencer's houses both moved from their foundations. The church building at Kahuku was badly ruptured. . . . —*From The Pacific Commercial Advertiser, April 4, 1868.*

. . . On Saturday, 28th, . . . at 1:23 p.m. (my watch), as I was standing at the gate of the Volcano House, the first heavy shock occurred, making me sway to and fro as if I had lost my footing, on a vessel's deck, rolling in a rough sea. . . . The (first) shock was felt throughout Kau, Puna and Hilo. At Keauhou the ground shook continually all the afternoon on Saturday. In Kau the shock seemed to have been stronger the more southward you went. At Waiohinu it shook down walls and cracked the stone church from top to bottom. At Kahuku, Captain Brown's place, the dwelling house, cattle pens, stone walls, etc., were thrown flat on the ground. . . . —*Letter from the School Inspector General, in the Hawaiian Gazette, April 29, 1868.*

A correspondent, writing from Kau, says:

. . . While at dinner (probably about 1:30 p.m.—Ed.) we had a heavy shock—crockery jingled and the house creaked like a ship in a storm. I left the table and went over to ——, and while talking with them we had a fearful shock. I caught up one child and —— another, and little —— and —— followed, running out of the house, while vases, books, lamps, boxes and dishes were falling about us. When we got out walls were falling down with a thundering noise, and the air was filled with dust—the earth still quivering. . . . —*From The Pacific Commercial Advertiser, April 11, 1868.*

In the Hilo District, at a place about ten miles north of Hilo village:

Kaupakuea, Hilo, March 29, noon (1868).

Mother earth has been quite lively since yesterday. The quakes commenced a little before noon and set the whole country rattling. They haven't done yet. Even as I write the house quivers and shakes like an old ship at sea, and outside the trees are politely bowing to each other. . . . The vacuum pan has a very perceptible sway, and the tall, iron chimney vibrates like a topsy-turvy pendulum. *The shocks are unlike our usual Hawaiian earthquakes (such as I have frequently felt before)—these being more deliberate, stronger but lazier, and longer continued.* . . . —*From The Pacific Commercial Advertiser, April 11, 1868.*

Probably the explanation of the peculiar character of the shocks noted by this observer, italicised by the present writer, is that these shocks were of more distant and deeper origin (beneath southern Kau) and of much greater total energy than the usual short, sharp Hawaiian shocks which he was accustomed to—shocks rarely felt at any great distance from the focal region, especially as strong shocks.

It is to be noted that this observer, though evidently careful and keen, even if somewhat rhetorical, does not speak particularly of the 1:30 p.m. shock, which implies that this shock was not especially noteworthy on the Hilo coast, though very strong in Kau, and notably strong in Puna and Kona. But it is possible, of course, that this is a lapse in observing on the part of the individual.

A letter of F. S. Lyman, dated March 31, 1868, states:

. . . The sensations of the hard earthquakes are peculiar—first are the hard shakes, then a swaying motion, as if the whole island were swaying back and forth, and we with it. . . . —*From The Pacific Commercial Advertiser, April 18, 1868.*

Mr. Lyman, at Keaiwa, near Kapapala, was still some twelve or fifteen miles distant from the epicentral region of the earlier hard shocks, and in lesser degree the explanation offered above will apply to the effects he notes.

THE EARTHQUAKE OF APRIL 2, 1868

GEOGRAPHICAL DISTRIBUTION OF APPARENT INTENSITY.

All accounts agree in indicating that *on land* this chief shock, at about 4 p.m. April 2nd, was most severe in the southern part of Hawaii. Its effects were of catastrophic order all the way from Waiohinu to the caldera of Kilauea, and so, probably, throughout the District of Kau. The earthquake was hardly less strong in large neighboring parts of south Kona and southwest Puna. It must have been strong at sea far to the southward of Hawaii. And there are strong suggestions that the energy in the neighborhood of the town of Hilo was but little less than in Kau. From this it would appear that very high intensity must have prevailed in the Hilo District southwestwards toward Kilauea, but this was an uninhabited tract.

Some citations of details are included below, but abundant accounts of the actions of this particular shock, *in its epifocal region,* have been given by previous writers. For the moment it is sufficient to state that the energy manifested on this occasion in the epifocal district has rarely been equalled, very rarely surpassed, by the action of powerful earthquakes.

Let us now look to some of the more remote areas in which this shock was felt. It was stated in the press, without contradiction, that it was felt throughout the group of the Hawaiian Islands, not excluding Kauai, almost the most distant of these, as the following extracts show.

A connected article published in *The Friend* of May 1, 1868, includes the sentence:

> . . . This was the moment when . . . the whole Islands shook and trembled.

Also, a carefully prepared account of the disturbance written, probably, by H. M. Whitney—who had especially visited Hawaii to investigate the disaster—then editor of *The Pacific Commercial Advertiser,* and published in that paper on May 9, 1868, states:—

> . . . while it was felt very sensibly on Maui, Molokai, Oahu and Kauai, the latter island 300 miles distant from the crater, . . .

Also, Mr. Whitney, writing from Kealakekua Bay on April 8, 1868, refers to

> . . . The earthquake, which was felt so distinctly on Oahu, Maui, and Kaui, . . .

Nevertheless, in the press accounts, no specific circumstance was related, nor was any Kauai letter quoted, to certify this prevalent statement that this shock was distinctly felt on Kauai.

However, it is very probable that the earthquake was distinctly perceptible there, and that these press references are therefore authentic, because the shock, or shocks, in the night of April 3-4, were not merely felt on Kauai but were strong enough to produce alarm among the natives, causing them to congregate about the dwelling of one of the white residents seeking protection and safety. This fact was related to the writer by a lady then resident there who was a witness of the circumstance.

Now Kauai is distant not less than 300 miles from the nearest part of Kau. Probably at least 350 miles intervened between the center of the epicentral region and southeastern Kauai. The shock occurred in mid-afternoon and, if distinctly perceptible, it must have reached an intensity of II-III Rossi-Forel or III Mercalli *at least*. Kauai is the most remote area from which reports of a *perceptible shock* on this occasion could come. Niihau was hardly farther away and at that time was not the place of residence of white men.

Next most remote is the island of Oahu. Here the shock undoubtedly was felt, probably throughout the island. As to the degree of intensity the accounts are not in strict accord. The following references have been extracted from the press:

> . . . felt so sensibly at Honolulu. . . . —*From The Pacific Commercial Advertiser, April 18, 1868.*
>
> Honolulu came in for its share of the earthquake on Thursday. At 4 o'clock p.m., the first occurred. It was very light, and was noticed mostly by those inside of stone buildings. The majority of our townspeople were not aware that a tremble had occurred. The motion was lateral and *quick* (motion structurally transformed (?)—Ed.). . . . —*From Hawaiian Gazette, April 8, 1868.*

At Honolulu:

> . . . the earthquake . . . occurred at 4 o'clock p.m., on Thursday, the 2nd inst., lasting about thirty seconds, with an undulating motion . . . —*From the Hawaiian Gazette, April 8, 1868.*
>
> . . . This was the moment . . . when the clocks stopped in Honolulu . . . —*From The Friend, May 1, 1868.*

The tidal wave reached Honolulu. It is discussed separately below.

It is difficult to reconcile the specific testimony of stopped clocks and the vaguer description of an undulatory shock perceptible for thirty seconds, with that which declares that it was very light, noticed mostly by those inside stone buildings, and unnoticed by a majority of the townspeople. Almost surely it varied in strength with the character of the ground, and very likely a large number of people were out of doors.

Considering the amount and character of motion undoubtedly required to stop clocks at the distance of Honolulu from the epifocal region, over 200 miles, an effect ordinarily considered to define grade VI R.-F. scale, it probably will not introduce error on the wrong side to adjudge an intensity of V R.-F. to the island of Oahu.

On Molokai:

It was stated both in the *Gazette* and in the *Advertiser* that this shock was felt on Molokai as, indeed, it must have been, but beyond this bare statement nothing has come to the writer's notice.

On Lanai and West Maui:

The island of Lanai and the western, maturely sculptured portion of the island of Maui are situated at approximately the same distance, 130 to 160 miles, from the epifocal region of this shock. As should be expected, the effects noted were of comparable character.

From Lanai, the following:

> . . . the shock . . . shook us on our pins on Thursday, the 2d inst., at about 3½ p.m. We heard boom, boom, and then we were shaken and rocked, and the crockery rattled in our cupboards. . . . —*From the Hawaiian Gazette, April 22, 1868.*

Judge Jones, of Lahaina, West Maui, communicated the following statement:

> About four o'clock, Thursday afternoon, there was an earthquake felt at this place. The room in which I was sitting at the time and the furniture in it, with the pictures hanging against the walls, shook, and clattered; at the same time a low, rumbling sound was heard, as if heavy carriages were passing along the road in front of the house. The shock lasted about 90 seconds. . . . —*From the Hawaiian Gazette, April 8, 1868.*

These accounts do not afford a good basis for judgment of intensity in terms of the R.-F. scale, but taken together with the facts preceding, and with those which follow, it seems legitimate to assign to Lanai and to West Maui an intensity of VII, R.-F.

On East Maui:

In East Maui, however, the shock was heavier. At Ulupalukua, on the southwestern slope of Haleakala, a recent lava cone showing only slight evidences of erosion, at a distance of 110 to 120 miles from the region of origin in a direction almost at right angles to the line between Hilo and Waiohinu,—

> . . . The vibration of Thursday was very strong, lasting nearly two minutes. Captain Makee reports that the cistern under his office, which was nearly full, swashed the water over its top, and that it was difficult to stand, the motion was so violent. The motion was from south to north. *Nine shocks were observed from the previous Saturday.* (This sentence is italicised by the present writer, incidentally, to point out that a deep origin and abundant total energy is indicated by this observation for several shocks prior to the chief culmination.—Ed.) . . . —*From the Hawaiian Gazette, April 8, 1868.*

From the fact, specifically cited, that the shock was so strong that it was difficult to stand—on the slopes of fresh lava on Haleakala

—even if a slight exaggeration, it seems sure that the intensity in East Maui could not have been lower than VII, R.-F., and that most probably it was low in the range of VIII of the R.-F. scale.

On Kahoolawe:

Nothing has been learned as to the behavior of the shock on Kahoolawe, but this island is distant from the epifocal region by about 120 to 130 miles, and probably it received a shock of practically the same power as East Maui.

This brings us to the island of Hawaii, in or near the southern part of which this shock probably had origin. The shore region of the Districts of Kohala and Hamakua are the parts of the island most remote from the epifocal tract.

For the following statement of its behavior at the Kohala Plantation, indicating in the judgment of the present writer intensity high in the range of grade VIII of the R.-F. scale, the writer is indebted to Mr. E. D. Baldwin, of Honolulu.

> Honolulu, T. H., March 31st, 1914.
>
> . . . Although the writer was only a boy of eight years of age at that time, the earthquake left a very vivid impression with him. We were at that time, about four o'clock in the afternoon, sailing boats in our circular fountain in front of our house (the manager's house at Kohala Sugar Co.), when the fountain seemed to be suddenly lifted and swayed back and forth by some mighty force from underneath, at first evenly in a northwest-southeast direction, and then in all directions.
>
> At first the ground rolled up into waves, coming evenly along in the same northwest direction, my impression being that the waves were from one to two feet high from trough to crest, then everything seemed to turn topsy-turvy, and we had hard work to keep balanced on our feet, but this seemed only for a moment, as with the same great rush, rumble and roar of noise, the earthquake passed quickly off in the direction of the Island of Maui.
>
> My father, D. D. Baldwin, then manager of Kohala Sugar Co., stated that the Kohala Mill chimney, a brick structure about one hundred feet high, had an old crack in it, which was widened out a little, and it might have fallen had it not been well bound with heavy iron bands. He also stated, the most notable incident showing the force of the earthquake in Kohala was that it stopped all the mill engines, even the large 75-horsepower engine which was running at the time with a full head of steam on. . . . —*Private communication addressed to the present writer.*

Coming closer to the region of origin at Kawaihae:

> . . . We learn from Captain Birrell that a strong shock was felt at Kawaihae on Thursday, the 2d inst., at about 4 p.m., lasting about thirty seconds. The motion was accompanied by a deep rumbling noise. Up the mountains to the north of the landing an immense cloud of dust arose, giving rise to the idea

that a fissure had opened, and that smoke and steam were mingled with the cloud. But it soon disappeared and was probably caused by the earth and soil falling from the steep sides of the Honopalo gulch, shaken down by the earthquake. . . . —*News item in Hawaiian Gazette, April 8, 1868.*

Also along the Hamakua coast, at approximately the same distance from the region of origin as Kawaihae:

> On Thursday at 4 p.m. Captain Ludlow, of the bark *Hibernia,* was off Hamakua, and experienced several shocks. It did not appear severe at sea, but must have been violent on shore. From the precipices which line the northern shore of the island, millions of tons of earth were seen falling down into the sea, loosened from the face of the cliffs by the force of the shocks.—*News item in the Hawaiian Gazette, April 8, 1868.*

The phenomena mentioned in the two reports immediately above are considered to indicate intensity of grade IX of the R.-F. scale, though probably the lower part of its range.

However, along the coast from Hamakua to Hilo, there was gradual increase in intensity, as the following quotation suggests:

> . . . Damage . . . to Hilo and vicinity. It shook down almost every wall in town; it cracked the basement of the Catholic church in several places; it knocked down ever so many (I think all) brick chimneys; . . . it knocked down the sugar house chimneys on the Spencer, Kaiwiki, and Onomea plantations; it caused ever so many landslides on the palis (cliffs) beyond Hilo, as far as Waipio, in Hamakua. . . . —*From a letter of the School Inspector General, published in the Hawaiian Gazette, April 29, 1868.*

At Hilo village:

> . . . I was coming from the tannery to my store, when I heard a loud rumbling noise like a number of iron carriages drawn over a rough road by wild horses. Soon the shock came. The horses in the pasture took fright, and ran and snorted, the dogs howled, and the pigeons flew about as if somebody had been shooting at them. The shock lasted a good while, how long I cannot say, but long enough to make me feel sea-sick, and it was with difficulty that I could stand. All the stone walls about the town were flat. Fissures opened and the brooks ran mud; in one place a fissure opened about a foot, and when it closed the two sides were several inches from coincidence.—*From the paper published by Dr. W. T. Brigham, in Memoirs Boston Society of Natural History,* 1, *iv, 1869.*

Hence at Hilo, intensity of the middle range, or higher, of grade IX of the R.-F. scale must have been manifested.

At Kealakekua, at about the same distance from the region of origin as Hilo, the effects were comparable, though possibly less, according to the following account:

> . . . I was on horseback. I reined in my horse at the commencement of the shock, and sat perfectly astounded. . . . Strong kukui trees were bent backward and forward, like reeds in a storm, not a breath of wind blowing at the time. . . . I saw a house fall, and large portions of two of the palis (cliffs). The walls were falling in all directions . . . no damage except to stone buildings and walls, some of the former being thrown down and nearly all of the latter suffering more or less. . . . —*From Mr. Williamson's letter in Hawaiian Gazette, April 8, 1868.*
>
> Cisterns of the Kona Plantation were cracked so as to be unfit for service without repair.—*News item in the Hawaiian Gazette, April 8, 1868.*

Great violence was manifested at sea, off the Kona coast, but the precise position of the observer is not given:

> Captain Hunting, of the whaling bark *Fanny*, was fifteen miles off the Kona coast on Thursday afternoon at 4 o'clock. Two shocks were felt, apparently at right angles with each other. The first was a vibrating motion, with a noise, as if the anchors and chain were running out over the bows. The second was perpendicular and so violent as to unseat him from the rail. The jib-boom was broken from plunging into the sea.—*News item in the Hawaiian Gazette, April 8, 1868.*

It would be conservative to consider such intensity a very high value under grade IX of the R.-F. scale.

This brings us to the District of Kau in southern Hawaii. Throughout Kau, and almost undoubtedly a large adjacent area of the ocean, together with a considerable area in western Puna, and lesser neighboring portions of the Hilo, Hamakua and Kona Districts, the intensity of this shock was very far above the lower limit of grade X of the R.-F. scale. Most of the phenomena occurring in this region have been described in many accounts, several of which were cited at the beginning of this study. There is no need to repeat this matter here. A single quotation, referring to Kapapala and also to the Kau coast at and southwest from Punaluu, will suffice to illustrate and justify the estimate of apparent intensity for the epifocal tract.

> . . . Nearly every wooden house at Keaiwa, Punaluu, Ninole and beyond were shot off their foundations or tumbled over, and straw houses with posts in the ground were torn to shreds. At Kapapala, the vault of the cistern (1700 barrels capacity) was shot off like a quoit, and the cistern itself smashed in and shut together so that not a vestige was to be seen of it. . . . —*From a letter of the School Inspector General, in the Hawaiian Gazette, April 29, 1868.*

ISOSEISMALS

No precise or intimately delineated isoseismal lines can be drawn for this shock, because nearly all the inhabitants of the island of Hawaii were located in settlements along the sea shore, or, as it happened, in a narrow strip of country extending through the epifocal tract in a straight line, almost, from the Volcano House at the crater of Kilauea to the village of Waiohinu; and reports from the other islands are too few in number and from points too widely separated to allow of detailed tracing of the lines. However, the isoseismals drawn on the accompanying map (Fig. 2) will appear to most readers reasonably located and traced with approximate accuracy, especially when it is pointed out that no made land, thick soils, or alluvial basins were concerned with the development of apparent intensity described above.

Assuming these curves, therefore, as sufficiently accurate, the tract characterized by intensity of grade X, R.-F. scale, has an elliptical shape with a major, N.N.E., diameter of not less than 100 miles, and a minor, W.N.W., diameter of not less than 60 miles, thus com-

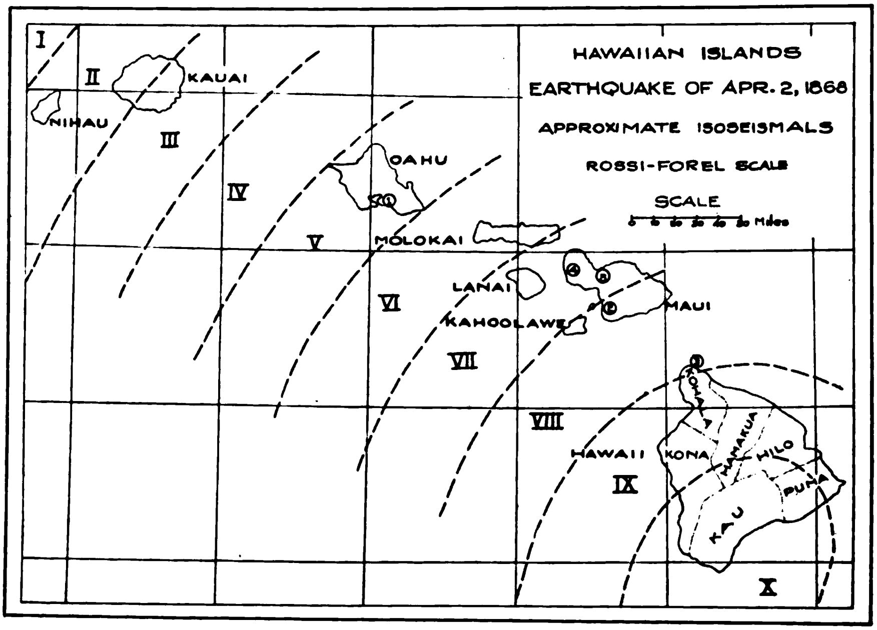

Fig. 2. (1) Honolulu; (2) Ulupalukua; (3) Kohala; (4) Lahaina; (5) Wailuku.

prising an area of about 4700 square miles, at least two-thirds of which lay beneath the ocean south and southwest of Hawaii, with the center of the tract in the sea south of Kau. Moreover, an intensity of IX, R.-F., was manifested all along the west and northeast coasts of Hawaii as far as Kawaihae and Waipio, the latter place at least 90 miles from the center of the epifocal tract.

If, as is believed, the shock was distinctly, though feebly, felt on Kauai, the area enclosed by the most remote isoseismal curve of perceptible intensity (outer limit of II, R.-F.), assuming it to be a circle of 350 miles radius, cannot be less than 375,000 square miles. It would not be surprising if the area were greater still. (The total land area of the Hawaiian group is a little less than 6500 square miles, or less than 2 per cent of the area of the region included by such an outer isoseismal curve). This area is comparable with, probably even greater than, that shaken perceptibly at the time of the destructive 1906 shock in California. The total energy, also, appears comparable with the total for the California shock, and probably somewhat greater, taking note of the violence of the action in the epifocal tract, and at more and more remote distance from it as well.

However, it may be, perhaps, that it is not legitimate to trace the isoseismal curves thus broadly over this great expanse of sea. Nevertheless, items cited in the record make it certain that the ocean floor and the deep water envelope which rests upon it, adjacent to the island of Hawaii, was powerfully shaken by this shock.

Hence there can be no doubt that, (*a*) the total energy manifested by this shock, as revealed by the nature and distribution of apparent intensity, was very great, undoubtedly placing the shock in the class of great earthquakes; and (*b*) that its origin must have been deep, or have extended to great depths, far greater than any characteristic of shocks consequent upon volcanic activity, as these have been defined, unless present conceptions of the radiation of seismic energy are greatly in error.

In both these respects the phenomena seem to accord well with the characteristics of great tectonic shocks, and ill with those of shocks of the volcanic class.

COSEISMAL METHODS ARE INAPPLICABLE

In the Hawaiian Islands by the generality of the population time has never been kept accurately, nor with reference to the standard meridian for the group, particularly at this early date, so that attempts to determine or use coseismal curves are wholly out of the question—even if the date were not so remote.

The Shocks of April 3-4, 1868

On Kauai, at the time of this disturbance, a shock experienced *in the night* was so strong as to shake dishes off from shelves. The native inhabitants unused to strong earthquakes, were badly alarmed and congregated about the house of a life-long resident of that island, who related these circumstances to the writer. This was near the southernmost part of the island. It is most probable that this shock occurred in the night of April 3-4, 1868. The intensity seems to have reached VI-VII, R.-F.

At Honolulu, and on Oahu:

> On Friday night we were visited again at 12:30 with another severe shock. The vibration was very perceptible, windows and doors rattled and many were awakened from their sleep. Another lateral shock occurred about 1 o'clock a.m., and two others before 2 o'clock.
>
> The same shocks were noticed at Kaneohe, and one planter rushed out to look after his sugar house chimney; no harm came to it. . . . *News item in the Hawaiian Gazette, April 8, 1868.*
>
> . . . Capt. Smith, at Waikiki, says of the earthquake on Friday night, the first shock at 12:30, midnight, undulating, lasting about 30 seconds, severe. Fifteen minutes after there was another, a tremulous motion lasting about the same time as the first. About two o'clock another occurred, heavy, with undulating motion, ending with a sudden jerk, as if a shell had burst under the house. The last shock was quick and short, being preceded by a short cessation of the undulating motion of the third one. . . . —*News item in the Hawaiian Gazette, April 8, 1868.*

On Oahu, therefore, the intensity of the strongest of these shocks seems to have risen to V-VI, R.-F., or possibly a little higher. There is strong suggestion also that the last shock emanated from an origin near this island.

On Lanai:

> . . . Again on Friday, the 3d inst., at about 3:15 a.m., we felt another earthquake. It awoke every islander from their slumbers. The earthwaves seemed to lift us up and toss us, as they rolled from east to west, keeping us moving and anxious for the space of about three minutes. . . . —*News item in the Hawaiian Gazette, April 22, 1868.*

While the foregoing accounts seem to the writer to be wanting in exactness (he is inclined to suspect that Saturday morning is really meant, that is, the night of Friday-Saturday), and to be exaggerated in tone—nevertheless, it is not improbable that an intensity of fully VII, R.-F., was developed.

At Lahaina, on Maui:

> There were two earthquakes at this place last night; the first occurred at nineteen minutes past twelve o'clock, and the other twenty-three minutes to one o'clock. The first lasted about thirty seconds and the other a little longer. They were both more violent (at Lahaina) than the one on Thursday (April 2), the latter more particularly so, and were attended with the same rumbling sound. My house was shaken violently. . . . —*News item, probably quotation from Judge Jones, in Hawaiian Gazette, April 8, 1868.*
>
> . . . The shocks of . . . Friday were felt at Wailuku, West Maui, also. . . . —*News item in the Hawaiian Gazette, April 8, 1868.*

An intensity of high VII or low VIII, R.-F. scale, probably prevailed on West Maui if these shocks were noticeably stronger than that of April 2nd.

These shocks were strong at Kawaihae on Hawaii:

> . . . The ship (the whaling bark *Fanny,* Captain Hunting) lay at Kaiwaihae Friday night. They experienced the same shocks which were felt that night on Maui and Oahu. They were so violent that the stone store and dwelling on the beach was abandoned by Mr. Conway. . . . —*News item in the Hawaiian Gazette, April 8, 1868.*

Surely an intensity of low VIII, R.-F., *at least,* is indicated.

But at Kealakekua shocks were noticed by the Rev. Mr. Williamson on April 4—at 12:29 a.m. VVH and at 12:45 a.m. VH, but without further comment.

And there are no reports of shocks of especially noticeable energy during this night from any observers in the Districts of Kau or Hilo.

The suggestion is obvious that at least three moderately strong earthquakes emanating from very considerable depths were generated in the sub-oceanic tract northwest of Hawaii during the early morning hours of April 4th, and that possibly one of these had its place of origin nearer to Kauai than to Hawaii. There is, of course, no strict proof of this. Moreover, the places of origin of these shocks cannot be indicated with any confidence and the meager data do not warrant any attempt to construct isoseismal curves. Nevertheless, it is reasonably certain that these shocks originated farther northwest, by many miles, than the region of origin of the great shock of April 2d.

The details for these shocks of April 4th have been cited chiefly

At Kawaihae:

> . . . Immediately an ebb and flow of the ocean commenced, the water leaving the reef bare, and coming in again, until reaching beyond high water mark. The sea ebbed and flowed thirteen times before regaining its usual equilibrium. . . . —*News item in the Hawaiian Gazette, April 8, 1868.*

At Lahaina, on Maui:

> About four o'clock the sea was observed to recede, and the space between the reef and the beach was left dry in many places. The sea ebbed and flowed thirteen times whilst I sat watching it and the time between each flow was between seven and eight minutes.—*Extract from a communication to the Hawaiian Gazette, April 8, 1868.*

At Honolulu:

> . . . Mr. Sterling observed the sea at quarter to six p.m. at low water; at six the flow had reached full half-tide, at quarter past six it ebbed to low water mark again. At twenty-five minutes to seven it flowed in again to full half-tide. Up to eight o'clock there were two oscillations and at ten o'clock the sea was again at high water mark. The usual tides at Honolulu are about three feet, with the moon two days its last quarter, but the sea during these movements rose and fell some five feet, even more than tides at full or change of the moon. The same flows were observed by Captain Daniel Smith, though his house is at some distance from the shore, the reef being alternately bare and again submerged by the water.—*News item in the Hawaiian Gazette, April 8, 1868.*

Careful reading of the foregoing items will discover that none of the reports referring to the southern coast of Hawaii states *explicitly* whether the sea first receded from or first invaded the shore region, though at first glance one of the accounts seems to declare that the first movement was towards the shore. This, however, is of small consequence since at places only a little more remote from the epicenter the first movement was a withdrawal of the waters. Moreover, a letter from Mr. Richardson, of Kapapala, in the *Hawaiian Gazette,* of April 15th, specifically stated that the waters first receded.

Such action forcibly suggests the subsidence of a sub-oceanic area, which would be the region of origin of the sea-wave, producing inflow toward the area, heaping of the waters, outrush of the wave, and subsequent oscillation. This suggestion is supported by the fact that a permanent subsidence of an area of the ocean floor south of Hawaii, visibly involving narrow portions of the former strand, took place at the time of this disturbance, the amount of subsidence near the shoreline being from four to seven (or eight) feet.[7] Previous subsidence had occurred here also, for Dr. W. T. Brigham,[8] in a paper read in 1866, says of the shore near Kalapana: "The sea is evidently advancing on the shore, as the stumps of cocoa-nuts are standing in the water half buried in the black sand which forms quite a steep slope above them." Yet there are no known native traditions referring to any catastrophic subsidences.

Now it appears to the writer that a sub-oceanic subsidence of sufficient amount and area to give rise to a seismic sea-wave of the magnitude indicated by the phenomena cited above, might well be considered a grand tectonic event—involving the fracture and dropping of a great crust-block (or major fault-block at the very least)—and such a movement would be abundantly competent to generate a great earthquake, quite apart from any accompanying volcanic hammerings. Indeed Professor Hitchcock,[9] though he expressly states in more than one place that he considers the shocks of this series to be of the volcanic type, refers to this subsidence as "(a place) where there may have been a species of tectonic movement," which, nevertheless, he deems "supplementary to the volcanic." The present study, however, aims merely at viewing the whole group of phenomena at another angle, without controversial intent. In any case it appears that this sub-oceanic subsidence is to be considered a tectonic event.

There remains to be considered the magnitude and extent of the rock-fissuring developed in the meizoseismal region.

> . . . The earth opened all through the district, and in some places caused dangerous fissures, while in others it closed up again. In one place it closed twenty feet from where it opened. . . . —*News item in The Pacific Commercial Advertiser, April 18, 1868.*
>
> . . . At Waiohinu, . . . a crack has opened from one to seven feet, extending to the beach and mauka (toward the summit) as far as the eye can reach. One remarkable feature of this is that the ends of the road, at the chasm are not opposite each other, one side having moved the width of the road mauka (towards the summit) or makai (towards the sea). . . . —*From Whitney's letter of April 8th, in The Pacific Commercial Advertiser, April 11, 1868.*

Here it is evident that there existed a strong horizontal component in a shearing strain which was partially adjusted, at least, by fracture and sidelong slipping.

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[7] *Bulletin Seismological Society of America,* **2**, 188-189.

[8] *Memoirs Boston Society of Natural History,* **1**, 374, 1868.

[9] *Bulletin Seismological Society of America,* **2**, 188.

It should be borne in mind that the fissuring here described occurred in the basalt rock of the mountain, not in soil alluvium or volcanic ejectamenta.

In an item in the *Hawaiian Gazette* of April 8th it is stated that this Waiohinu fissure was impassable. In 1868 the trails were traveled almost exclusively by saddle animals, hardly if at all by wheeled vehicles. Hence if the statement is not a gross exaggeration this fissuring must have been deep, wide and extended,—to have stopped the progress of the Hawaiian mountain-bred horses.

> . . . At Kahuku, back of the church, is a hole sixty feet in diameter, the bottom of which cannot be seen. . . . —*News item in The Pacific Commercial Advertiser, April 11, 1868.*
>
> . . . Between Richardson's (Kapapala) and Kilauea . . . a wide opening of the earth has occurred, in some places twenty feet wide, and miles in length, from which smoke and steam rise and in which fire is seen. . . . —*News item in The Pacific Commercial Advertiser, May 2, 1868.*

From a letter written by Dr. Wm. Hillebrand, a man of scientific attainments in botany, relating to the fissures near the Puna-Kau trail:

> . . . Where the Puna road turns off from the Kilauea road (near Kapapala), heavy clouds of white vapor were seen to issue from the bush . . . (south of the trail). Half an hour's ride brought us up to the place, but we were obliged to leave our horses some distance before reaching the spot, on account of fissures. After having crossed a number of them, heading for the heaviest cloud of vapor, we at last came to a deep crevasse in the pahoehoe, at least twenty-four feet in width, no bottom visible. It narrowed and widened out in places, but nowhere was less than eight feet wide. Its length we estimated at four hundred feet. Parallel with this great crevasse, constituting a belt six hundred feet in width, were a number of smaller ones on each side, diminishing in size with distance from it, from six feet to a few inches. . . .

This description relates to what is only a conspicuous locality in a curving line of deep fissures, open to the present day, many of which were generated during this seismic spasm of 1868 (some, however, are of earlier date). This line extends from the crater of Kilauea, at least, to the sea at a point about east of Pahala. Horizontal dislocations of considerable amount took place at this time between the east and west margins of the fissured tract, indicating here also a marked horizontal component of shear.

Hitchcock quotes Fornander, writing of events at and near Punaluu,—

> . . . A big chasm opened running from the sea up into the mountain

> (Kilauea), down which, it is said, lava, mud, trees, ferns, and rocks were rushing out into the sea. . . .

Further from Dr. Hillebrand's letter (italics introduced by the present writer) relative to Mauna Loa:—

> . . . Here (at Kahuku) the lava burst forth, April 7th, through an enormous fissure of nearly three miles in length . . . *the great fissure having been formed, in all probability, on April 2d, the final breaking through of the lava seems to have begun almost without noise.* . . .
>
> This crack or fissure tends south six degrees west to north six degrees east, *and is in the slope of the hill that forms the west boundary of the lava stream.* . . . Its depth cannot be ascertained anywhere.
>
> Having arrived at the apex of the triangle (the head of the flow) I found that the crevasse, over which the trees almost closed from both sides, still extended a few hundred yards higher up in the woods, as indicated by a continuous line of white and yellow smoke. [Dr. Hillebrand was prevented by the impenetrability of the jungle as well as by the choking fumes from exploring the course of this fissure higher up the mountain than the head of the flow. Hence the careful reader will note that the fissure may have extended much farther up the mountain than Dr. Hillebrand asserts. Some have stated, but upon what basis of observation is unknown to the present writer, that a belt of fissures, opened at this time, extended to the very summit.]
>
> . . . I saw two other lines of smoke running through the woods, . . . indicating two other fissures. Thus it appears that at the head of the valley the main fissure divided itself into three parts; the first, and largest, running northeast; the middle one almost due north; and the third about north-northwest. The two latter did not seem to have thrown off much lava if any, for there appeared no gap in the woods along their courses.

From a letter of the Rev. Titus Coan written to Dr. W. T. Brigham under date of August 27, 1868. (The italics are introduced by the present writer):

> . . . From the landslide (at Kapapala) I went on to the igneous eruption in western Kau. *Rents, tiltings and other disturbances of the strata were seen along the shore,* while the wooded and grassy hills on the right (the southeastern soil-covered slopes of Mauna Loa) were scalped, scarred, cracked, and striated. . . .

(Then, referring to the flow from Mauna Loa:)

> . . . This portion of the eruption went into the sea about one mile northwest of Ka Lae, the south cape of the island. On the left (east) flank of the streams is a high and very steep ridge (four hundred to five hundred feet high) extending from the cape up the southern slope of Mauna Loa. The outburst of April 7 commenced about ten miles from the sea by the opening of a horrid fissure in the forest on the upper (east) side of the precipice. For about

> three miles the burning river flowed down partly above (east) and partly below (west) this precipice. The area above was rich and beautiful land for cultivation and pasturage; that below (west) was simply pahoe hoe. The four lateral streams . . . (reached first in going westward from Waiohinu) all ran off upon the highland.

Also from Professor Hitchcock's book:[10]

> The land runs to a point at the extreme south end of Hawaii. . . . The triangular area—perhaps nine miles long—from the ranch house to the sea, is bordered on the west side by a precipice or pali, suggesting that it lies along the line of a fracture. This impression is heightened by the fact that the line coincides with and adjoins the rent of three miles (Hillebrand) out of which the lava (of 1868) was protruded. . . . Mr. Whitney seems to have observed the coincidence in the direction of the pali (cliff) and the vent of the eruption pointing up the mountain. So did Mr. Coan. In 1886 I visited this locality and called attention to the feature in a letter to Professor Dana, published in his "Characteristics of Volcanoes."
>
> The fissure whence the lava of 1868 flowed is in exact continuation of the pali (cliff) up the mountain. I traced it fully three miles. For much of the way it makes a narrow cañon forty to fifty feet wide at the maximum, and so deep that it is dangerous to explore it. (All this in 1886.—Ed.). . . .
>
> The connection of the fissure with the pali (cliff) shows clearly the existence of a fissure along its whole length which has been the seat of eruptions in ages past. . . .

The present writer would add that this great fracture has obviously been the locus of vertical fault slips for ages past as well. Also, that there is abundant geological suggestion that the Kilauean fissures as well, described earlier, are associated with a great line of rifting that appears to cut completely across the island of Hawaii from the neighborhood of Waiohinu to the neighborhood of Hilo, and passes through, or tangent to, the western part of the caldera of Kilauea.

Such fissures as are described above have occurred in connection with volcanic eruptions in other regions as well as here. It is, of course, possible that they are intimately concerned with the mechanism of eruption, as apart from regional strain.

However, it does not immediately and directly follow that they must be due to volcanic potential properly so-called, that is, gas-tension, magmatic tumescence, the momentum-pressure of rising magma bodies, etc. Indeed, it is difficult, though perhaps not impossible, to conceive how volcanic potential could generate a horizontal component of shearing strain as strong as, or stronger than, the vertical component in the shell of the volcanic dome. But such shearing strains were manifestly built up in the surface rock of both Kilauea and Mauna Loa, and partially relieved on this occasion.

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[10] "Hawaii and Its Volcanoes," Honolulu, 1909, pp. 108-109.

CONCLUSION

The writer feels that it is idle to speak dogmatically, or to attempt generalizations concerning natural phenomena when there is not overwhelming weight of favorable evidence without important contradictory, or unexplained, data. Arguments have been advanced for considering these earthquakes as volcanic shocks. It has seemed profitable to re-examine the facts with the possibility of a tectonic origin, so-called, as distinct from a volcanic origin, so-called, in mind. It seems to the writer that the hypothesis of tectonic origin will bear analysis as well as, if not better than, the hitherto accepted hypothesis of volcanic origin. More than this is not asserted definitely.

Moreover, in view of the phenomena which were developed in this series of shocks, and particularly of the sub-oceanic shocks originating northwest of Hawaii; and in view of the prehistoric subsidence at Kalapana, the inland line of fault-cliff along southeast Hawaii, the bold precipices of the Kohala coast, and the great rift lines and collapse-calderas of both Kilauea and Mauna Loa, together with analagous phenomena in the other islands, it seems to the writer a hazardous scientific practice, as well as one charged with potential danger to life and property, to assert that these islands stand in no danger from tectonic earthquakes, or to encourage the spread of such opinion.

If the view that these shocks constitute a tectonic crisis finds acceptance, we shall need to review our conceptions of the mechanism and modes of causation of so-called volcanic earthquakes, with the purpose of delimiting and defining more precisely this type, if, indeed, such a type exists in reality apart from earth-strain from tectonic causes, and we shall need to review our conceptions of the mechanism of volcanic eruption also, at any rate in certain specific cases.

Hawaiian Volcano Observatory,
August 24, 1914.

THE INFLUENCE OF EARTHQUAKE DISTURBANCES ON SUSPENDED MAGNETS[1]

By HARRY FIELDING REID

Horizontal Movements.—It has long been known that magnets are sometimes caused to oscillate by earthquake disturbances; a phenomenon which has given rise to much discussion. If an ordinary body were suspended at its center of gravity it would be in equilibrium in whatever direction it might be turned. If it were suspended by a fiber attached to any other point, its center of gravity would lie immediately under the fiber; and a to and fro motion of the support would introduce forces which, passing through the center of gravity would produce a pendular vibration of the body, but no oscillation about a vertical axis.[2] Is it possible that a magnet could be caused to oscillate by a movement of its support? We note that a magnet is not an ordinary body; if it were suspended at its center of gravity it would be in equilibrium only when its magnetic axis lies in the direction of the lines of force of the magnetic field. These lines, horizontal at the earth's magnetic equator, dip more and more in higher latitudes, until they become vertical at the magnetic poles. If a magnet is held in a horizontal position in the northern hemisphere the vertical component of the earth's field tends to raise the S end and to lower the N end; that is, it exerts a moment to turn the magnet. This moment is usually balanced, for suspended magnets, by placing a small weight at the S end of the magnet or by displacing the point of suspension to the north; the center of gravity now lies slightly south of the line of suspension, a moment equal and opposite to the vertical moment is introduced, and the magnet remains horizontal.

If the support is moved, a force is introduced which does not pass through the center of gravity, and therefore a moment is set up about the center of gravity, and the magnet swings as a pendulum and also oscillates about a vertical axis. Evidently, then, if a magnet vibrates as a pendulum, an oscillation will necessarily occur. And, if a magnet oscillates it will also vibrate; for it would naturally tend to oscillate about its center of gravity; the point of attachment of the fiber would be displaced and a pendular vibration be set up. Therefore neither type of motion can exist without the co-existence of the other.

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[1] This is a repetition of a paper published under the title "The Free and Forced Vibrations of a Suspended Magnet," in *Terrestrial Magnetism and Atmospheric Electricity,* 1914, **19**, 57-72, 189-203, the mathematical part being replaced by explanatory paragraphs.

[2] We shall use the word *vibration* to indicate the swing of the magnet like a pendulum, and *oscillation* to denote an oscillation about a vertical axis of the kind that might be caused by magnetic forces.

The distance between the center of gravity and the line of suspension is very small;[3] and therefore the moment tending to produce an oscillation in the way described is extremely small; but if the periodic movement of the support, caused by earthquake vibrations, has the period of the pendular swing or of the magnetic oscillation of the magnet, the effect is cumulative, and quickly becomes large enough to be appreciable. The periods of both the vibration and oscillation of the magnet will always be the same as that of the exciting disturbance.

In magnetic observatories continuous records from three kinds of magnets are kept: (1) the *unifilar* magnet is one suspended by a single fiber (of the kind we have discussed above), and is used to record the changes in the horizontal direction of the magnetic lines of force; (2) the *bifilar* magnet is supported by two fibers, the line connecting the upper ends of which is turned through an angle in order to hold the magnet in an east-west line; this form records variations in the intensity of the horizontal magnetic force; (3) the *magnetic balance* is a magnet balanced horizontally in the magnetic meridian on knife-edges; it records variations of the vertical magnetic force.

So far as small displacements are concerned, the bifilar magnet will react like the unifilar, because the resultant of the tensions of the two fibers will be exactly equal to the weight of the magnet and will lie in the line we have called the line of suspension in the case of a unifilar magnet; that is, it will not pass through the center of gravity of the magnet; and these relations will hold whether the actual positions of the two fibers be or be not symmetrical with respect to the line of suspension, or to the center of gravity. A bifilar magnet therefore cannot vibrate without oscillating, and cannot oscillate without vibrating; and oscillations with increasing amplitudes will be set up by mechanical vibrations of the support having either one of the two natural periods of the magnet.

The center of gravity of a magnetic balance lies a little below and

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[3] For a particular magnet of the U. S. C. & G. Survey, used to determine magnetic force, the distance is only about 0.05 mm.

(in the northern hemisphere) a little to the south of the supporting knife-edge; a periodic mechanical movement of the support will introduce forces acting through the knife-edge and will set up periodic moments about the center of gravity, which will cause large oscillations of the magnet if they have the natural period of the magnetic oscillation.[4]

We see, therefore, that all these forms of recording magnets can be set in oscillation by a periodic horizontal movement of the support. An east-west movement will be most effective for a unifilar magnet, a north-south movement for a bifilar magnet or for a magnetic balance.

Vertical Movements.—In 1860 Melde[5] showed that a stretched string could be set in strong transverse vibration by a longitudinal movement of its end with a period half that of the transverse vibration. Lord Raleigh[6] pointed out that this principle applied to many kinds of vibrations, and especially that a pendulum could be made to vibrate through a large arc by a properly-timed vertical movement of the support. The period of the disturbance is half that of the vibration. This experiment can easily be repeated. Hold in the hand a string with a weight fastened to it, and start it swinging gently. As the weight leaves its position of equilibrium raise the hand, and as it approaches it lower the hand; the amplitude will continually increase. The action of the forces in increasing the amplitude is clear. As the weight leaves its lowest point, it is raised by the increase in the tension of the string over the force of gravity, and its motion is not at right angles to the string; so that its velocity is not destroyed by gravity as rapidly as with a stationary support. As the weight falls, gravity increases its velocity on account of the relaxation of the string, and it falls a greater distance on account of the lowering of the support. It therefore arrives at its lowest position with a greater velocity than when it last left it; a continuation of this process increases the amplitude indefinitely, and the greater the amplitude the more rapidly it increases. It is necessary that there should be an initial swing, for purely vertical forces could not originate horizontal movements. But a small swing is practically certain to be produced whenever a pendulum is disturbed by outside forces.

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[4] See further under Vertical Movements.

[5] Ueber Erregung stehender Wellen eines fadenformigen Körpers. *Pogg. Ann.* 1860, **109**, 193-215; **111**, 513-537.

[6] *Philosophical Magazine*, 1883, **4**, 229-235.

When a unifilar magnet is subjected to vertical displacements whose period approaches half the natural period of pendular vibration of the magnet, it will be set into pendular vibrations; and, as we have seen, when a magnet vibrates as a pendulum, it necessarily also oscillates as a magnet. But it is not found that a magnetic oscillation will be developed when the period of the vertical displacements approaches half that of magnetic oscillations; for the tension of the fiber is always at right angles to the plane of oscillation, and therefore cannot directly affect the oscillation. It is only indirectly, by setting up pendular vibrations, that vertical displacements can cause oscillations of the magnet.

When a bifilar magnet is subjected to vertical displacements of the proper period, pendular vibrations and corresponding oscillations are developed just as in the case of a unifilar magnet. When the magnet is at rest at right angles to the magnet meridian, the turning moment due to the horizontal magnetic force is balanced by the opposing moment due to the twist of the fibers. A periodic vertical displacement will vary the tension of the fibers and thus periodically vary the latter moment, and directly cause oscillations. If, therefore, the period of the vertical displacement approaches one half the period, either of the pendular swing or of the magnetic oscillation, the magnet will be set into oscillation with increasing amplitudes.

As has been pointed out, the center of gravity of a magnetic balance lies a little below and, in the northern hemisphere, a little to the south of the supporting knife-edge; it is quite evident that a vertical movement of the support and a horizontal movement in the meridian would affect the magnet in the same way. The mathematical theory shows that the oscillations set up will become large if the period of the movement (horizontal or vertical) approaches either the natural period of oscillation of the magnet or one-half this period.

Experiments.—In order to test the conclusions reached the following experiments were made: A magnet was suspended by means of a light copper wire stirrup and a cocoon fiber in a wooden box, similar in a general way to the ordinary case of a magnetometer. A small plane mirror facing west was fastened to the stirrup immediately above the magnet, and deflections were observed by means of a telescope and scale. The box rested on two round brass rods, so that it could easily be moved in an east-west direction. To show that an east-west pendular swing is always accompanied by magnetic oscillations having the pendular period, the box was suddenly moved a short distance to the west. A pendular swing was immediately started, and on looking through the telescope the scale appeared to move lineally in a direction making a small angle with the vertical. The vertical movement measured the angular displacement of the pendular swing, and the horizontal movement measured the magnetic oscillation; the former was about ten times as large as the latter. As the two movements combined into a linear movement, their periods were absolutely the same, and corresponded to the period of the pendular swing. There was also seen a small horizontal oscillation having the magnetic period, with an amplitude about equal to that of the magnetic oscillation with the pendular period. These results are in satisfactory quantitative agreement with the theory.

As the interplay of the two kinds of vibrations depends on the separation between the center of gravity and the line of suspension, and as this separation depends on the vertical component of the earth's magnetic field, and disappears with it, the interplay should cease if we should annul the vertical component, and a movement of the support should then develop a pendular swing only and no magnetic oscillation. To annul the vertical force two long magnets were fastened to the movable support, one above and one below the suspended magnet, and so placed as to develop a vertical magnetic force about equal, and in the opposite direction, to the vertical component of the earth's field. The adjustment was far from perfect, but on suddenly displacing the support as in the former experiment, the magnetic oscillation was only 1/20th or 1/30th of the pendular swing.

The attempt was then made to set up a magnetic oscillation with the magnetic period by moving the support back and forth in this period by hand. The estimated range was 3 mm.; the period was checked by a metronome, and the movement was kept up for six complete periods. The theory shows that the amplitude attained should be about 24′; an oscillation was set up, but its amplitude was only about 8′. This difference apparently was due to the impossibility of keeping the exact period, and to irregularity in the movement; the latter also was the cause of a larger pendular swing than the theory calls for. On repeating the experiment with the magnets annulling the vertical force in place, no material reduction in the amplitude of the oscillation produced was noticed. The cause of this discrepancy was not clear. It is possible that a better agreement in period was realized in the last experiment, and that the controlling magnets were not properly placed; but the facilities and time at my disposal did not permit me to clear this up. I am convinced that with proper arrangements the theory would be entirely confirmed.

The difficulty of arranging for a vertical vibration prevented the testing of this part of the theory, but the simple experiment of setting a pendulum swinging by properly timed vertical movements of the support can easily be tried by any one, and the first experiment above makes it clear that, if the pendulum is a suspended magnet, a magnetic oscillation with the pendular period will also be produced. A very short experience with a suspended magnet having a movable support will impress any one with the ease with which magnetic oscillations can be produced by simple mechanical disturbances.

Under vertical displacements, the bifilar magnet, in addition to acting like a unifilar, is, as has been shown, also influenced by a special turning moment due to the fact that there are two suspending fibers. The characteristic moment produced can readily be exemplified with an ordinary non-magnetic bar. Hang the bar to a pencil or to one's finger, by two parallel strings, and start it oscillating; as it approaches its position of equilibrium, lower the support; as it leaves it, raise the support; the oscillation will increase at first slowly, and then more rapidly. A little consideration will show that we are practically dealing with an ordinary pendulum under peculiar conditions; or, perhaps it might be better to say, with two pendulums attached to each other and moving in opposite phases.

Historical.—It has long been known that magnetic needles are sometimes made to oscillate by near or distant earthquakes; but the phenomenon is much more general than is usually realized. Very many, perhaps all, severe earthquakes, and some that are not severe, set recording magnets into oscillation. The Riviera earthquake of February 23, 1887, disturbed magnets at many observatories from Lisbon to Vienna and from the south of France to England and northwest Germany.[7] The California earthquake of April 18, 1906, disturbed magnets in the observatories of Honolulu, Sitka, Baldwin (Kansas), Toronto, Cheltenham (Maryland), and Porto Rico.[8] Many other instances might be cited.

The Riviera earthquake gave rise to much discussion of this phenomenon. Mascart[9] could not understand how a simple shaking of the support could excite the oscillations of a magnet; he states that the observed disturbances were not like the usual magnetic perturbations, but resembled more nearly the disturbances due to the momentary electric currents which made the time marks on the record, but continued for a longer period; that is, the disturbance was due to an oscillation whose period was to be measured in seconds rather than in minutes. Mascart believed the disturbances of magnets at various observatories was simultaneous, in spite of the difference in distance from the origin of the earthquake; and he suggested that electric currents, which disturbed the magnets, were set up at a particular phase of the earthquake.[10] But it is difficult to understand how currents could be produced; and Moureaux attempted to decide between the mechanical and electric or magnetic theory by setting up on the pier supporting the horizontal component, or bifilar magnet, a copper bar of the same form (and presumably of the same size), mounted in the same way, and with the same orientation. At the time of subsequent earthquakes the bifilar magnet oscillated but the copper bar did not; Moureaux and Mascart thought this result precluded a mechanical explanation of the phenomenon.[11] If they had made the rather obvious reverse experiment of shaking the supports of their magnet, and of their copper bar, they would have found that an oscillation of the magnet could be set up by mechanical vibrations, and that an oscillation of the copper bar could not, and they probably would have cleared up the whole subject.

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[7] Davison gives a map showing thirteen observatories where magnets were set into oscillation by this earthquake. "A Study of Recent Earthquakes." London, 1905, p. 158.

[8] "The California Earthquake of April 18, 1906," **2**, 139.

[9] *Comptes Rendus*, 1887, **104**, 607-608.

This problem has engaged the attention of many other distinguished magneticians, who in general have concluded that the oscillation of the magnet was due to mechanical vibrations; they based their conclusion on the fact that the magnet was affected at the time of the arrival of the earthquake vibrations, and on the character of the record. This explanation seems first to have been advanced by the astronomer F. Carlini in 1842. He thought the oscillation was due to a "simple mechanical shock communicated to the center of gravity of a needle hung by a very fine wire," and proposed to test this idea by setting up a heavy pendulum to determine if the pendulum and the magnet would be disturbed at the same time. Agamennone, who reports Carlini's suggestion, states that the seismographs installed later confirm Carlini's idea.[12] Among others who have adopted this explanation, without attempting to show how a mechanical vibration could produce an oscillation of the magnet, may be mentioned Wild,[13] Eschenhagen,[14] Messerschmitt,[15] and Bauer.[16] While Bauer was in charge of the magnetic work of the United States Coast and Geodetic Survey, seismographs were installed in the magnetic observatories of the Survey for the purpose of comparing their records with those of the recording magnets. An interesting account of this comparison was given by Burbank,[17] from which it appears that the two classes of instruments did not always record the same disturbance; some earthquakes recorded by the seismographs were not recorded by the magnetographs, and *vice versa;* in other cases both instruments recorded the same disturbance. The magnetic record usually consisted of a broadening or blurring, or even interruption, of the photographic trace, indicating oscillations too rapid to be recorded separately; but another class of magnetic disturbance seemed to be associated with some earthquakes, namely, small periodic oscillations with periods of two or more minutes. These, I believe, were first noticed by Moos in Bombay at the time of the great Assam earthquake of June 12, 1897.[18] Farr[19] gave a more careful description of similar movements recorded at Christchurch, New Zealand. Both writers considered them magnetic. They were also noted by Burbank. They deserve careful study. It is strange that the period of the waves on the declinometer record at Christchurch was 130 seconds and on the bifilar 41.5 seconds. No explanation is offered of this curious difference. The natural periods of oscillation of the two magnets were 10.34 and 13.07 seconds, respectively.

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[10] The committee of the French Academy appointed to study the Andalusian earthquake of December 25, 1884, arrived at about the same conclusion. "Mission d'Andalousie," *Mem. Acad. Sci.*, Paris, 1889, 30, 11-16.

[11] Sur les relations qui peuvent exister entre les perturbations magnétiques et les tremblements de terre du 30 Mai 1889. Letter of M. Moureaux to M. Mascart. *Comptes Rendus*, 1889, **108**, 1189. Sur la cause de certains troubles observés sur les courbes des magnétographes. *Comptes Rendus*, 1889, **109**, 272-274. See also same, p. 660.

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[12] I terremoti le perturbazione magnetiche. G. Agemennone, *Rend. d. R. Acad. d. Lincei,* 1893, Ser. 5, **2**, 479. See also "Supra la correlazione dei terremoti con le perturbazione magnetiche"; same, 1890, Ser. 4, **6**, 21-26; where Agamennone attempts to explain Moureaux's results by showing that a bifilar magnet is more sensitive to a turning moment than a non-magnetic bar; but he does not explain how a turning moment is developed.

[13] *Comptes Rendus,* 1889, **109**, 164-166.

[14] "Erdmagnetismus und Erdbeben." *Sitz. Akad. Wiss.,* Berlin, 1894, pp. 1165-1172.

[15] "Beeinflussung der Magnetographen-Aufzeichnungen durch Erdbeben und einige andere terrestrische Erscheinungen," *Sitz. K. Bayer, Akad. Wiss. Math.-Phys.* Kl., 1905, **35**, 135-168.

[16] "Magnetograph Records of Earthquakes, with Special Reference to the San Francisco Earthquake," *Terrestrial Magnetism,* 1906, **11**, 135-144.

[17] "Earthquake Disturbance Recorded on the Magnetographs at the Observatories of the U. S. Coast and Geodetic Survey, No. 1," *Terrestrial Magnetism,* 1905, **10**, 113-125.

[18] See *B. A. A. S.* 1898, Report on Seismological Observations, 240.

[19] "Records of Earthquakes in Quickly-Driven Magnetographs." *Terrestrial Magnetism,* 1902, **7**, 193-195.

There are two investigators who threw much light on our problem. In 1885 Charles Davison[20] pointed out tentatively that one end of a compass-needle would receive a greater effective impulse than the other at the time of an earthquake shock on account of its greater mass; he did not consider a magnet suspended by a fiber. Later he explained the different responses of Moureaux's bifilar magnet and copper bar by stating that in order that the magnet may rest in a horizontal position, its center of gravity must be at unequal distances from the two points of support.[21] Though neither of these explanations is strictly accurate, still I think the credit is due to Davison of having first perceived the true cause of the oscillation of magnets under earthquake movements.

In 1895 J. Liznar[22] gave a perfectly correct explanation of the oscillations of a unifilar magnet and of a magnetic balance due to an earthquake; but in his explanation of the oscillation of a bifilar he deals with causes of the second order of small quantities, and overlooks the more important displacement of the center of gravity due to the vertical component of the magnetic field. He expressly excludes vertical movements as a cause of the oscillation of unifilar and bifilar magnets.

These two important papers seem to have been almost entirely overlooked. Writers on seismology, such as Milne, De Montessus de Ballore, etc., do not refer to Davison's paper at all; and where Liznar has been mentioned there is no intimation that he has made any important addition to our knowledge of this subject. Neither paper was known to me until my study of magnetic oscillations due to horizontal mechanical disturbances was finished.

Milne with his accustomed industry, investigated this subject.[23] He collected reports from many magnetic stations and compared them with the times of recorded earthquakes. This statistical method can not, of course, yield an explanation; it is capable only of suggesting one. And, as was to be expected, Milne's results are inconclusive. He found great differences at different observatories, some reporting many disturbances of the magnets at the times of earthquakes, others much fewer. He suggests that this may be due to more or less synchronism between the periods of the magnets and of the earthquake waves, but finds no satisfactory confirmation of this idea. He also sought a relation between stations which reported many magnetic responses to earthquakes, and gravitational anomalies, but his results were wholly indecisive. A rather curious fact reported is that magnetographs mounted in Toronto were less affected by earthquakes than after they were removed to Agincourt, a few miles away.[24] On the whole, Milne's investigation, though bringing together many observations on the subject from widely scattered regions, threw no real light on the cause of the phenomenon.

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[20] "On a Possible Cause of Disturbance of Magnetic Compass-Needles during Earthquakes." *Geol. Mag.*, 1885, Dec. III, **2**, 210-211.

[21] "A Study of Recent Earthquakes," 161, footnote.

[22] "Einfluss des Erdbebens vom 14 April 1895 auf die Magnetographen in Pola und Wien nebst einigen Bemerkungen über die Wirkung der Erdbeben auf magnetische Variations-Apparate überhaupt," *Meteor. Zeitschr.*, 1895, **12**, 261-267.

[23] *B. A. A. S.*, Report on Seismological Investigations, 1898.

Conclusions.—It has been shown in this paper that both horizontal and vertical mechanical vibrations are capable of causing oscillations of recording magnets; and, in particular, that there are two periods for horizontal and one for vertical disturbances which will cause marked oscillations of a unifilar magnet; that there are two periods for horizontal and ~~two~~ three for vertical disturbances that will cause marked oscillations of a bifilar magnet; and, finally, that there are two periods for horizontal and two equal periods for vertical disturbances which will cause marked oscillations of a magnetic balance. The period of the disturbance must be very close to the proper value in order that the effect may be cumulative, in order, therefore, that a disturbance of small amplitude may make a clear record in the magnetic trace; and this seems to be one reason why the responses of recording magnets to earthquake disturbances are so variable. A careful comparison of the natural periods of the magnet and the periods of the earthquake vibrations which set it in oscillation would be necessary in order completely to establish this relation.

If two magnets are subjected to a mechanical shaking for the same length of time, and if the period of the disturbance is, in each case, exactly the magnetic period of the magnet acted upon, the amplitudes developed will be different if the natural periods or other constants of the magnets are different. There is such a great variety in the periods and other constants of magnets recording in various observatories, that they must be very differently sensitive in their responses to earthquake disturbances.

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[24] "Seismological Observations and Earth Physics," *Geog. Jour.*, 1903, **21**, 15-18.

There are three other ways, which may be called fortuitous, by which magnetic oscillations may be caused mechanically: (1) the damping of the magnet may not be symmetric; (2) a magnet of the Eschenhagen form which is confined in a copper damping box, may, when swinging, strike against the box and be set in oscillation; and (3) a magnet, especially one with unifilar suspension, may be tilted about its point of attachment in its own vertical plane, thus displacing its center of gravity; and then a movement at right angles to the former would introduce a moment which would cause oscillations.

There are so many ways by which oscillations can be produced mechanically that we are led to the conclusion that the broadening, blurring, or sudden interruption of the magnetic trace at the time of earthquakes is due to oscillations of the magnets caused by purely mechanical vibrations, and does not require us to assume the existence of real magnetic forces or electric currents; and, moreover, that the differences in the periods and other constants of the recording magnets in actual use account, probably sufficiently, for their various responses to earthquake disturbances.

THE EARTHQUAKE IN THE SANTA CRUZ MOUNTAINS, CALIFORNIA, NOVEMBER 8, 1914.

By CARL H. BEAL

About 6:30 p.m. on the eighth of November a short, and in some places rather severe, earthquake was felt generally throughout the Coast Ranges of California from Santa Rosa in Sonoma county southeast to Soledad in Monterey county, and as far east as the San Joaquin valley. An intensity of III, Rossi-Forel scale, was estimated at Santa Rosa, III at Soledad, and II at Fairmead in the San Joaquin valley. Correspondents report that it was not felt as far north as Ukiah, or as far south as San Luis Obispo.

The area affected was not large, and in order to try out the plan of locating the epicenters of our California earthquakes from personal observations, it seemed worth while to gather on the ground such information in regard to intensity as could be had of people who felt the shock. Only about twenty observations and notes were sent in to the Seismological Society of America, the small number probably being due to the fact that the area of highest intensity is in a thinly populated part of the Santa Cruz mountains. About half of the data obtained in this way were furnished by the Spring Valley Water Company of San Francisco. The writer therefore spent four days in the field, and gathered from the people themselves most of the information contained in this brief account. Some information was also obtained by writing directly to acquaintances.

It was evident almost from the first that the intensity was higher in Santa Clara county than it was in San Francisco. A report from Dr. Horace Davis in San Francisco suggests an intensity of about III, while President Branner and Dr. Townley estimated that the shock at Stanford University had an intensity of from IV to VI, Rossi-Forel scale.

An interesting and valuable contribution to the subject was obtained from the experience of a young lady on the campus at Stanford University who was conversing with another lady in San Francisco at the time of the shock. The lady at Stanford felt the disturbance and remarked that she would have to hang up the receiver on account of the earthquake; the lady at the San Francisco end of the line said that no shock had been felt there, and immediately exclaimed, "Here it is now!" Evidently the wave had passed from the direction of Stanford University toward San Francisco.

The work in the field consisted of the gathering of notes from observers. Many persons were consulted at Stanford University and in the towns of Palo Alto, Mountain View, Santa Clara, and San Jose, and trips were then made to Alviso, Saratoga, Los Gatos, Wrights, Laurel, Glenwood, Skyland, Soquel, Aptos, Watsonville, Gilroy, Morgan Hill, and Coyote. At Watsonville and Gilroy the intensity was estimated at IV, Rossi-Forel scale, but as San Jose was approached the intensity seemed to rise, and in the town of Los Gatos it was evidently much higher than in the city of San Jose.

At Los Gatos the observations of Mr. Snyder, member of the Seismological Society of America, were obtained, and the accompanying record of his seismograph was kindly furnished by him. Mr. Snyder makes the following comments on the record:

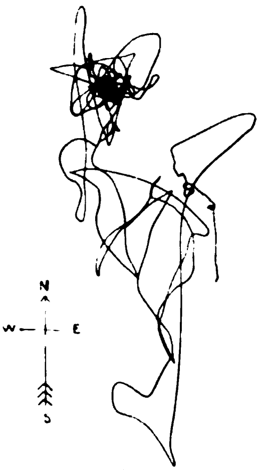

Fig. 1. Seismographic Record (enlarged four times). Los Gatos, Cal., Nov. 8, 1914. By Irving H. Snyder.

"The seismograph gives some idea of the actual horizontal motion of the earth during the shock, except that the machine enlarges the record to four times that of the real movement. There was also considerable vertical motion, of which no record was made. The maximum motion in a north to south direction was a little less than half an inch, and occurred very close to the beginning of the shock.

This is shown on the right in the record, where the long line extends straight downward to the lowest point. Two small loops, seen near the upper portion of this line, mark the actual beginning of the shock. The upper part of the record shows the movement as the vibrations diminished to zero."

In the town of Los Gatos considerable damage was done, though in no case was it serious. At least six chimneys and two or three window panes were cracked. Small amounts of plaster fell in three houses, six clocks were stopped in the town, and chinaware and bric-a-brac were thrown down. A few showcases in the stores were broken by bottles and canned goods falling from the shelves.

In the Santa Cruz mountains six or seven miles south of Los Gatos the shock was more severe, but did less damage, probably because of the scarcity of houses. At Laurel, where the intensity seems to have been highest, two chimneys were broken off and a number of articles fell from the shelves in the grocery store. A number of clocks were stopped, and at one place it was observed that the kerosene in one lamp was violently agitated while that in another twelve feet away had not a ripple on the surface. A similar occurrence was noted four miles northwest at Mr. Van Lone's place, where a small commode was overturned and milk in pans a few feet distant was undisturbed. One mile north of Laurel near the fault line (see Fig. 2) the plaster was badly cracked, and large quantities of it were shaken to the floor. At Terrace Grove a fireplace made of large rounded stones was badly cracked, and one man was thrown to the ground.

The seismograph at Santa Clara University recorded the earthquake shock at 6:31:09 p.m. At Lick Observatory, Mt. Hamilton, it is reported to have begun at about 6:31 p.m., and the actual duration as recorded by the seismograph was 4 minutes 35.2 seconds.

Almost half of the people consulted in regard to the earthquake claim to have heard a low rumble not unlike that of distant thunder, and three or four people within the area of the highest intensity describe the noise as a loud roar. The remainder of the observers report that no noise was heard. At San Francisco, Berkeley, Millbrae, Niles and Palo Alto the noise was reported to have been a low-toned rumble, and at Los Gatos, New Almaden, Coyote and Palo Alto observers state that the noise preceded the earthquake by one or two seconds and continued throughout the duration of the shock.

The earthquake was described by some as a sharp circular jerk preceded by a slight tremor, and by others as a prolonged jolt with

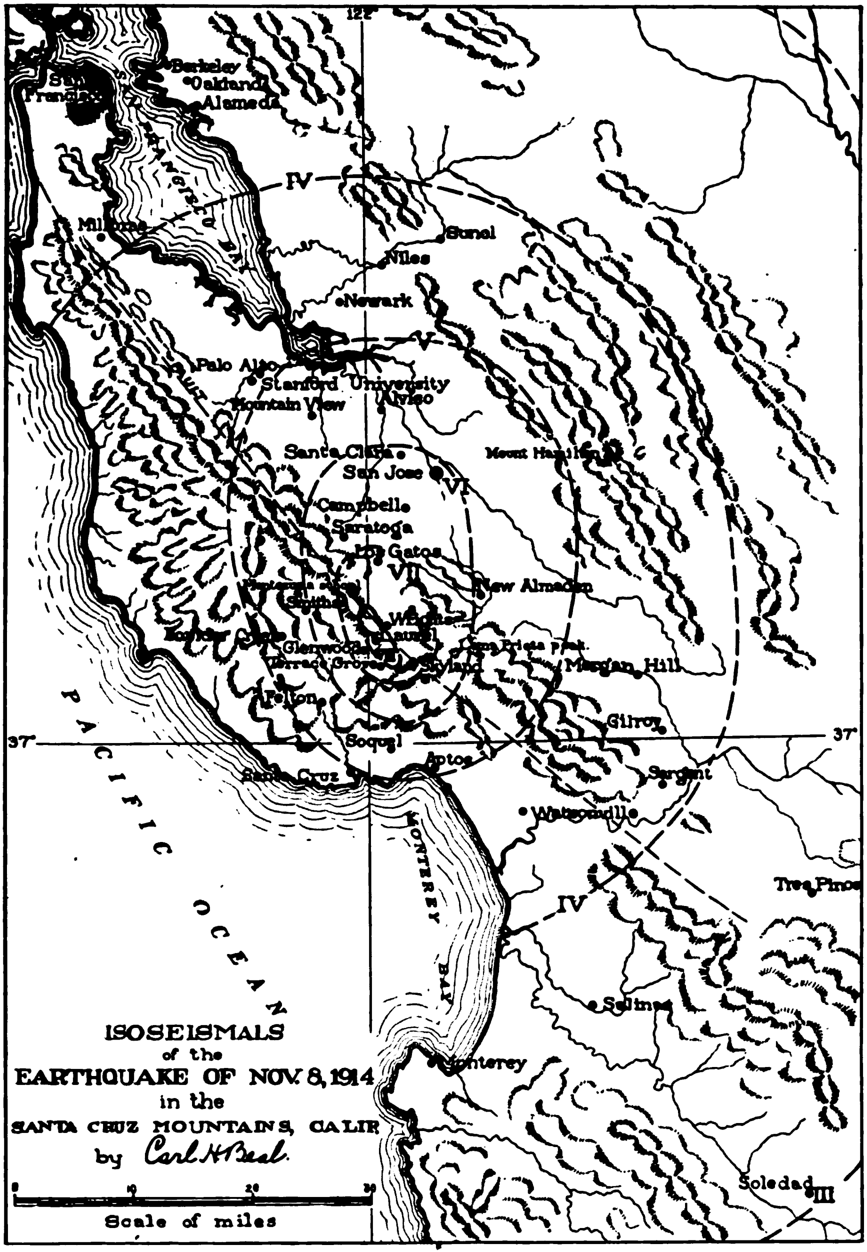
ISOSEISMALS
of the
EARTHQUAKE OF NOV. 8, 1914
in the
SANTA CRUZ MOUNTAINS, CALIF
by Carl H Beal
0
10
20
30
Scale of miles
122°
37°
37°
IV
V
VI
VII
IV
III
PACIFIC OCEAN
SAN FRANCISCO BAY
MONTEREY BAY
Berkeley
Oakland
Alameda
San Francisco
Millbrae
Sunol
Niles
Newark
Palo Alto
Stanford University
Mountain View
Alviso
Santa Clara
San Jose
Mount Hamilton
Campbell
Saratoga
Los Gatos
New Almaden
Smith
Wright
Laurel
Glenwood
Terrace Grove
Skyland
Morgan Hill
Loma Prieta peak
Felton
Gilroy
Soquel
Aptos
Santa Cruz
Sargent
Watsonville
Tres Pinos
Salinas
Monterey
Soledad

Fig. 2.

two, and perhaps three, distinct maxima of intensity, with the motion of the last at right angles to that of the first. At Mt. Hamilton the earthquake began with a feeble tremor for three or four seconds, suddenly turning into a strong jolt, and gradually diminishing for one or more minutes.

The epicenter of the disturbance was near the small town of Laurel, close to the crest of the Santa Cruz range, and about seven miles south and one mile east of Los Gatos. About the epicenter the intensity was as high as VIII Rossi-Forel scale. The town of Laurel is one mile southwest of the San Andreas-Stevens Creek fault, along which the movement occurred at the time of the earthquake of April 18, 1906. Though no surface evidence was found of movement on this fault line on November 8th, it seems probable that some deep-seated movement on or close to the fault caused the recent shock. This belief is further strengthened by the fact that at the Montezuma School, about four miles northwest of Laurel and approximately on the fault line, two water pipes were broken.

The accompanying map shows most of the district over which the earthquake was felt, and the isoseismals by the Rossi-Forel scale are estimated from the data collected in the field.

Stanford University,
November 28, 1914.

SEISMOLOGICAL NOTES

Kingston, Jamaica, August 3, 1914.—Our colleague, Mr. J. F. Brennan of the Public Works Office at Kingston, sends us a brief account of an earthquake at that place on August 3, 1914. The shock cracked several brick walls, and was generally felt. The extreme horizontal movement as recorded by the seismograph was just one inch.

Two other shocks were recorded that same day—one at 7:24 a.m. with a movement of 0.25 inch and lasting four seconds; another at 10:24 a.m. with a movement of 0.002 inch.

Mr. Brennan reports another shock at Kingston, Jamaica, on August 19th. It was sufficiently violent to cause the recording needle of the seismograph to jump the plate, but no other notes are given of that shock.

Olympia, Washington.—The following is quoted from the *Olympia Recorder* of September 5, 1914:

"Olympia and this part of the state was soundly jolted and jarred at 1:35 this morning by an earthquake shock. First sensation was a tremor or vibration, then came a sharp and severe jolt and rocking motion that jarred the houses, making loose articles rattle, many report. Within two minutes after the shock the telephone central here was getting reports.

"The quake was felt at Tacoma, Puyallup, Sumner, Auburn, and other points. No report was received here today as to the seismograph records at the university in Seattle."

Konieh, Turkey, October 3, 1914.—A violent earthquake in the province of Konieh, Turkey, is said to have destroyed more than three thousand lives. This shock was mentioned in the September number of this BULLETIN, but there was doubt about the date of it. Later information shows that the epicenter was in the vicinity of Burdur and Isbarta, and both of those towns were completely destroyed. The line of the railway from Smyrna to Aidin was somewhat damaged.

Kingston, Jamaica, October 14, 1914.—A fairly sharp shock was felt at Kingston, Jamaica, at 2:15 a. m. This was followed by smaller shocks at 3:05 a.m. lasting one second; another at 3:32 a.m. lasting one second; and still another at 11:45 p.m. lasting one second. The principal shock gave a record of 0.45 inch, and was felt all over the island of Jamaica. We are indebted to our colleague, Mr. J. F. Brennan of the Public Works Office at Kingston, for these notes.

Thebes, Greece, October 17, 1914.—A violent earthquake occurred at 8 a.m. October 17, 1914, in the Grecian provinces of Attica and Boetia. Thebes was seriously damaged, most of the buildings being destroyed and many lives having been lost. Much damage is said to have been done in the neighboring towns. At Athens several houses had their walls cracked. In Boetia some twenty separate shocks were noted. The disturbance was also felt in many of the adjacent islands.

Lassen Peak, October 23, 1914.—An explosive eruption of Lassen Peak, Shasta county, California, on October 23, 1914, at 6:30 a.m. is said to have been accompanied by rumblings and slight earth tremors. A column of smoke rose to a height estimated to be about ten thousand feet, and ashes fell over the mountain sides.

Lucca, Italy, October 26-27, 1914.—Several earthquake shocks were felt at Lucca, Italy, on the 26th and 27th of October, and less severely at Turin, Genoa, Florence, Pisa, Bologna, Venice, and other towns of northern Italy. No particular damage was done, though there was more or less panic among the inhabitants. The fall of a large piece of the cornice of the castle in which Queen Margarita was living caused much alarm, but no other damage was done. The most severe shock was at 10:20 a.m. on the 27th. The epicenter was near Lucca or between that city and Bologna.

Shabatz, Servia, October 27, 1914.—The newspaper reports of the war in Servia mention an earthquake at Shabatz, a town on the Save river west of Belgrade, on October 27th. The city is said to have been shaken hard enough to threaten the fall of houses already damaged by fire and by bombardment.

Vina, California, November 6, 1914.—Two shocks are reported at the town of Vina, about twenty miles north of Chico, California, at 7:25 p.m. No damage was done.

Los Angeles, California, November 8, 1914.—At 3:40 p.m. an earthquake was felt at Los Angeles, California, and in the surrounding towns. Several persons state that it was accompanied by an explosive sound. No damage has been reported.

Santa Cruz mountains, November 8, 1914.—The details of this shock are given in an article in this number by Mr. Carl H. Beal.

Santa Clara valley, November 21, 1914.—At about 8:30 a.m. a slight shock was felt at and about San Jose and Santa Clara. It was recorded at the observatories at Mt. Hamilton and Santa Clara.

Western Greece, November 27, 1914.—Considerable damage to buildings and more than twenty deaths were caused by an earthquake in northwestern Greece and the Ionian islands on November 27th. The highest intensity seems to have been on the island of Santa Maura.

New Seismic Station in the Western Pacific.—Rev. M. Saderra Masó, S. J., has kindly sent the following note concerning a new seismological station:

"With the consent of the Naval authorities in Washington and with the most effective cooperation of the Governor of the Naval Station of the Island of Guam, Captain W. J. Maxwell, U. S. N., the Manila Observatory has had the opportunity of installing a seismograph at Agaña, Island of Guam.

"For many years past the Director of the Observatory had been anxious to have a good registering seismograph on the Island, because, owing to its proximity to the Challenger Deep, its seismic condition is extremely interesting.

"Last August a Weichert seismograph of 180 kilograms was mounted by Rev. M. Saderra Masó, Assistant Director of the Weather Bureau, in a room excellently adapted for the purpose, in the Government House, at Agaña. An officer and mechanic of the Naval Station were instructed in the use and regulation of the instrument, and they were left in charge.

"The situation of the new station is 144° 45′ Long. E., and 13° 20′ Lat. N. The instrument is about twenty feet above sea level, and is built on ground composed of hard madreporal rock.

"It is expected that this station will furnish very excellent data concerning the shocks which originate in, or in the vicinity of, the Challenger Deep."

REVIEWS

HARVARD SEISMOGRAPHIC STATION. FIFTH ANNUAL REPORT INCLUDING RECORDS, 1 August 1912–31 December 1913. By J. B. Woodworth. *Bulletin of the Museum of Comparative Zoology*, **55**, no. 3 (Geological Series, **9**, no. 3), pp. 55-77, 1914.

This is a continuation of the list of earthquakes given in *Bulletin of the Museum of Comparative Zoology*, **55**, 22-52. It contains the records of 110 shocks occurring between August 1, 1912, and December 31, 1913; eleven of these are reported as doubtful.

Only three earthquakes were recorded the origin of which was within the United States and adjacent portions of Canada. These are: The Williams, Arizona, earthquake, August 18, 1912; the South Carolina earthquake, January 1, 1913; the earthquake north of the St. Lawrence River, April 29, 1913.

It is curious that the two noticeable earthquakes that occurred in New England, viz. earthquake of December 11, 1912, felt from Augusta, Maine, to Fredericton, N. B., and that of November 3, 1913, in southwestern Rhode Island, were not registered by the instruments of this station.

C. F. TOLMAN.

LE CASE CHE SI SFASCIANO E I TERREMOTI. By G. Agamennone. *Revista di Astronomia e Scienze affini*, September 1913.

This title, "Houses which fall in ruins and earthquakes," was given to an article by Professor G. Mercalli printed in the *Rassegna Nazionale*, January 1, 1885, in which he points out the danger in the lofty and poorly constructed buildings which are to be found in the larger cities, such as Milan, Rome, and Naples; and to another article, by the same author, printed February 1, 1913, in the same periodical, in which he says that the government should see to it that buildings be made safe, and this before, rather than after, disaster by earthquakes; that no one should be allowed to construct excessively high buildings, especially in the neighborhood of low ones; and that builders should not be allowed to use cheap material nor cheap labor.

Professor Agamennone adds that public and private buildings should be inspected at regular intervals, to make reasonably sure that they are capable of resisting earthquakes, and that new buildings should be constructed under proper supervision. The regulations should be more or less severe, according as the region in question is more or less subject to earthquakes.

While this would cause considerable expense, yet the expense of proper construction and repairs would be less than the loss of property by earthquakes would be otherwise, to say nothing of the loss of life.

At present many new buildings are not properly constructed, and many older ones are on the point of falling in ruins. The government inspects temporary tiers of seats erected at race tracks and the like. It would be much more desirable for it to inspect these permanent structures.

If the cost of repairs to old structures would be too great to admit of putting any regulations in force, at least all new buildings should be properly constructed. (See the September 1914 number of this periodical, p. 165, the review of an article in which the author develops this idea.)

C. G. ALLEN.

ÜBER ERDBEBENWELLEN. VIIA BEOBACHTUNGEN AN REGISTRIERUNGEN VON FERUBEBEN IN GÖTTINGEN UND FOLGERUNGEN ÜBER DIE KONSTITUTION DES ERDKÖRPERS. By B. Gutenberg. *Nachrichten der K. Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse.* 1914. pp. 1-52.

This paper is a continuation of six contributions on the subject of earthquake-waves by Steichert, Zoeppritz, Geiger and Gutenberg, and especially of contributions V and VI on the constitution of the earth's crust.

Observations on the transmission-time of various earthquake waves and the intensity relations of longitudinal earthquake-waves are recorded. It is shown that one may take for longitudinal and transverse waves of great epicentral distances two similar velocity components as functions of the depth, so that they agree with the observed intensity relations as well as with the observed times of transmission.

There is proof of a new very strongly marked plane of instability in the earth's crust. Finally, the period of the first preliminary tremors of earthquakes of great epicentral distance were investigated.

A. F. ROGERS.

THE REGISTRATION OF EARTHQUAKES AT THE BERKELEY STATION AND AT THE LICK OBSERVATORY STATION FROM OCTOBER 1, 1912, TO MARCH 31, 1914. By E. F. Davis. *University of California Publications, Bulletin of the Seismological Station,* Nos. 5, 6, 7, pp. 97-153.

These three numbers of the Bulletin of Seismographic Stations of the University of California have been issued during 1914. Number 5, covering the period from October 1, 1912, to March 31, 1913, contains the records of twenty-seven earthquakes registered at the Berkeley Station and one hundred and three registered at the Lick Observatory Station. Special mention is made of only one of these shocks, that of October 25, 1912. Concerning this shock Mr. Davis makes the following statement on page 116 of the report:—

> This earthquake was peculiar in that it appears to have been a double shock,—that is, the disturbance consisted of two separate earthquakes, occurring one after the other and separated by a short interval of time.
>
> At the Lick Observatory the record is clearly that of two separate shocks. No. 33 in the record of Lick Observatory is the first shock and is the more intense of the two. No. 34 is the second and less intense earthquake. On the seismogram the first preliminaries of the second shock are merged with the end portion of the first shock. This earthquake was not generally felt at the Lick Observatory, but those who did feel it described it as a swaying motion. No report is made of feeling two separate shocks or of two maxima in the motion as felt at this station.
>
> At Santa Clara two separate shocks were felt, the first at 3h. 16m. 14s. and the other about 3h. 20m.
>
> The distance of the Berkeley Station from the origin was considerably greater, and here the movement of the ground due to the first and more intense shock is prolonged over such an interval that the record of the weaker shock is lost in the record of the first (No. 5, Berkeley Station). At this station, therefore, the seismogram gives no evidence of two separate earthquakes.

Bulletin No. 6, covering the period from April 1 to September 30, 1913, contains the records of twenty-one shocks registered at Berkeley and seventy-one registered at the Lick Observatory. There is special discussion of three of these shocks—those of May 30, June 26, and September 9, 1913.

Bulletin No. 7, October 1, 1913, to March 31, 1914, contains the records of thirty-four shocks registered at the Berkeley Station and seventy shocks at the Lick Observatory Station. Special mention is made of three of these disturbances, those of October 25, 1913, the San Bruno shock of January 24, 1914, and the Reno shock of February 18, 1914.

S. D. TOWNLEY.

SEISMOLOGICAL REPORTS RECEIVED

AMERICA

Harvard University, Cambridge, Mass., U. S. A.—Records of the seismographic station, from September 1 to November 1, 1914.

Ottawa, Canada. Earthquake Station, Dominion Astronomical Observatory.—Reports nos. 19 and 20, September 1 to October 31, 1914.

PHILIPPINE ISLANDS

Manila, P. I.—Seismological Bulletin of the Observatory, nos. 22 to 24, July 1 to 31, 1914.

EUROPE

Stonyhurst College Observatory.—Earthquake records by Milne seismograph, September 2 to October 28, 1914.

Granada, Spain.—Boletin mensual de la Estacion sismologica de Cartuja. No. 8, August 1914.

Nachrichten des Taunus-Observatoriums des physikalischen Vereins zu Frankfurt am Main.—Nos. 5, VI*a*, and VI*b*. May 8 to June 27, 1914.

Monatsberichte der Haupstation für Erdbebenforschung zu Jena. September 28 to December 30, 1912.

Geophysikalisches Institut Göttingen.—Nos. 19-26, May 7 to June 29, 1914.

ASIA

Żi-ka-wei (China).—Bulletin Sismique, nos. 7 to 8 bis, 10 and 10 bis. May 25 to August 22, 1914.

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ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

I. **Microseismic shock**: recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. **Extremely feeble shock**: recorded by several seismographs of different kinds; felt by a small number of persons at rest. some startled persons leave their dwellings.

III. **Very feeble shock**: felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. **Feeble shock**: felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.

V. **Shock of moderate intensity**: felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.

VI. **Fairly strong shock**: general awakening of those asleep, general ringing of house bells; oscillation of chandeliers; stopping of pendulum clocks; visible agitation of trees and shrubs; some startled persons leave their dwellings.

VII. **Strong shock**: overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. **Very strong shock**: fall of chimneys. cracks in walls of buildings.

IX. **Extremely strong shock**: partial or total destruction of some buildings.

X. **Shock of extreme intensity**: great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

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ERRATA

Vol. 1, page 89, line 27: for Sieperg's read Sieberg's.
page 89, line 28: for Erdhehenkunde read Erdbebenkunde.
Vol. 2. page 41, line 32; for Kiangsi read Kiangsu.
page 42, line 28; for I read 4, and for II read 5.
page 43, line 6; for V read 4, and for VI read 5.
page 81, figure 2; the curve for North China should be continuous, instead of broken, from August to October.
page 82, table VII: in the part for North China in the column headed Sep., for the first two numbers, 5 and 6, read 7 and 5; and in the totals, same column, for 12 read 21; and in the net totals for 11 read 20. In the part for Central China, net total for June, for 12 read 13. In the part for South China in column headed Sep. in second number, for 1 read 0; and in totals and net totals for same column, for 8 read 7.
page 83, line 34; for VI read II.
Vol. 3, page 6, line 24; for southern read southeastern.
page 11, line 34; for evidences read evidence.
page 12, last line; for Seismologlcal read Seismological.
plate 4, opposite page 125; interchange the printed lines under the two illustrations.
page 126, line 18; for five read fine.
page 220, and Vol 4, pages 52, 102, 168: after line 16 insert, ping of pendulum clocks; visible agitation of trees and shrubs; some startled persons leave their dwellings.
Vol. 4, page 89, line 29; for 14 read 13.
No. 2, back cover, line 18; for a read the.
page 117, line 13: for 2:55 p.m. read 4:55 p.m.
page 131, line 11: for acceession read accession.
page 144, line 14, below table: for as read so.
page 159, line 36: for 5:54 .m. read 5:54 a.m.
page 159, line 46: for 2:35 .m. read 2:35 p.m.
page 160, line 40: in last column insert E. H. G.

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